The Potential of Agroforestry Systems to Mitigate the Effects of Climate Change

Writing assignment

Environmental Biology

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Samenvatting

Het globale klimaat verandert op een alarmerend tempo als gevolg van menselijk handelen welke heeft geleid tot een toename van de uitstoot van broeikasgassen en veranderingen in landgebruik en landbedekking. Terwijl landbouwactiviteiten een grote impact hebben op ons klimaat, zijn landbouwactiviteiten wel afhankelijk van een gunstig klimaat. Deze verbintenis tussen landbouw en ons klimaat zorgt ervoor dat boeren zullen moeten aanpassen om de weerstand van landbouw tegen klimaatverandering te vergroten. Gezien de negatieve impact van de conventionele industriële landbouw op onze omgeving en klimaat, groeit het besef van de noodzaak om een vorm van duurzame landbouw aan te nemen, terwijl er nog steeds wordt voldaan aan de stijgende vraag voor voedsel als een gevolg van bevolkingsgroei en veranderingen in voedingsgewoonten. In Agroforestry, of boslandbouw, wordt er doelbewust gebruik gemaakt van het combineren van een landbouwgewas of het houden van vee met bomen en/of struiken op hetzelfde perceel. Deze vorm van landbouw komt naar voren als een krachtig instrument in de landbouwsector om deze aan te passen aan een veranderend klimaat doormiddel van natuur inclusieve aanpak. Deze literatuur review heeft als doen een allesomvattend overzicht te creëren over het potentieel van boslandbouw om bij te dragen aan het verbeteren van ecosysteemdiensten in de landbouw van de gematigde klimaatzones, met name in Europa. Deze informatie is juist nodig over de gematigde klimaatzones omdat dergelijke systemen meer worden toegepast in het mondiale zuiden en onderzoek hierover dus makkelijker verkrijgbaar is. De reden hiervoor is wellicht dat rond de tropen hedendaags meer gebruik wordt gemaakt van traditionele landbouw vormen. Door gebruik te maken van een rigoureuze en transparante methodologische aanpak worden in deze review recente ontwikkelingen binnen de boslandbouw uitgewerkt, met specifieke aandacht voor bodemorganische koolstof opslag en biodiversiteit functies. Deze punten zijn uitgekozen om de hoge klimaat mitigerende effecten en buffercapaciteiten. Boslandbouwsystemen leggen koolstof vast in de bodem door deze uit de atmosfeer te absorberen. Een hogere koolstof vastlegging in de bodem zorgt voor gezondere bodems welke resulteert in een langdurige stabiliteit waardoor een landbouwsysteem meer weestand heeft tegen extreme weersomstandigheden als een gevolg van klimaatverandering. Ook een hogere biodiversiteit helpt hierbij door te werken als een buffer doordat zij belangrijke habitatten aanbieden en connectiviteit tussen natuurgebieden verhogen. Onze analyse biedt een overweldigende ondersteuning voor de gunstige effecten van boslandbouw op zowel deze koolstofopslag als biodiversiteit. Wij bieden in deze review een antwoord op de ecosysteem diensten die geleverd worden door boslandbouw ten opzichte van conventionele agricultuur, met implicaties voor klimaat mitigerende mogelijkheden en aandachtspunten voor in de toekomst. De positieve gevonden resultaten plaatst boslandbouw als een belangrijke benadering in het mitigeren van de effecten van klimaatverandering, waarbij de nadruk ligt op het potentieel om koolstof effectief op te slaan en vast te leggen, evenals het herbergen van een grote hoeveelheid biodiversiteit. Uit de bevindingen van deze review kan er geconcludeerd worden dat boslandbouw systemen over het algemeen grotere opslagcapaciteiten van organische koolstof hebben in vergelijking met hun monocultuur tegenhangers. Bovendien tonen ze een groot potentieel om een hoge soortenrijkdom te herbergen en de multifunctionaliteit van landbouwsystemen te verbeteren door een toename van natuurlijke bestuiving en plaagbestrijding. Niet alleen ondersteund boslandbouw deze diensten, maar gebeurt dit ook bij een lagere plantdichtheid, wat kan worden toegeschreven aan de onverstoorde aard van deze systemen en hun grotere groeiruimte. Hierom zijn beheersregimes, zoals snoei frequentie en recreatie, en de leeftijd van systeem belangrijke succesfactoren in boslandbouw.

Contents

Abstract

The global climate is changing at alarming rates as a consequence of human activities that led to increased greenhouse gas emissions and land use and land cover changes. As agriculture is intrinsically linked to climate conditions, farmers will need to adapt to enhance climate resilience. Due to the negative impacts of conventional industrial agriculture on our environment and climate, there is a growing recognition of the need of sustainable agricultural production meeting rising demand due to population growth and dietary shifts. Agroforestry emerges as a powerful tool in the agricultural sector to mitigate and adapt to a changing climate. This review aims to offer a comprehensive overview of the potential of agroforestry to contribute to enhance ecosystem services in temperate climatic zones, Europe in particular. By employing the rigorous and transparent methodologies of a literature review, we focus on recent developments in agroforestry with specific attention to soil organic carbon (SOC) and biodiversity. Our analysis provides overwhelming support in the literature for the beneficial effects of agroforestry on both carbon storage and biodiversity. From our findings we can conclude that in general, agroforestry systems have larger SOC pools when comparing them to their monoculture counterparts. Furthermore, they show great potential to harbour high species richness and enhance agricultural systems' multifunctionality through increased pollination and pest control. Not only does agroforestry support these services, but it does so at lower planting densities, which could be attributed to the undisturbed nature of these systems and their larger growing space. Hence, management regimes and age of a system are important success factors in agroforestry. These promising results positions agroforestry as a crucial approach in mitigating the effects of climate change, emphasizing its potential to store and sequester carbon effectively as well as harbour a great amount of biodiversity.

Keywords: *agroforestry, agriculture, silvopastoral, hedgerows, carbon storage, carbon sequestration, biodiversity, pollination, pest control*

Introduction

The global climate is changing at an alarming rate as a consequence of human activities that led to an increase in greenhouse gas emissions, and land use and land cover change. The combined effect of both is an increase in global temperatures resulting in the destabilisation of ecosystems. An overwhelming amount of evidence presented by scientists through extensive monitoring of global climatic conditions and predictive modelling is making it increasingly clear that our environment is changing and demands an urgent global response. From the records of global temperature measurements since the preindustrial era, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that the current global mean surface temperature is roughly 1.1 °C higher than the 1850-1900 average (IPCC, 2023) with Europe warming faster than most other parts of the world by over 0.3°C (IPCC, 2013). They state that "*global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years*". Along with these direct climatic measurements, a quantification of Röckstrom's Planetary Boundaries have been calculated by Richardson et al. (2023). The planetary boundaries framework delineates nine crucial processes essential for preserving the stability and resilience of the entire Earth system. It formulates the limits of a safe operating space which when exceeded passes the Earth's tipping point. Currently, all of these processes are significantly disrupted by human activities (Richardson et al., 2023). These boundaries are all, directly or indirectly, affected by today's agricultural practices. In particular, these boundaries include those for biodiversity, climate, and nutrient cycling (N and P).

Climate change has diminished food security and impacted water security, impeding endeavours to achieve the Sustainable Development Goals (IPCC, 2023). Since agriculture is highly dependent on climate, farmers will need to adapt to enhance climate resilience and mitigate its effects on climate change by reducing their emissions (Hernández-Morcillo, 2017). Today's conventional agricultural methods, such as row crop agriculture, are extremely intensive and efficient at maximising yields. This intensification has led to enhanced productivity through the use of external inputs such as fertilizers and pesticides, but also given rise to numerous environmental issues (Mosquera-Losada et al., 2018). Due to the negative impacts of conventional industrial agriculture on climate change, there is a growing recognition of the need for sustainable food, fodder, fibre, and fuel production to meet the rising demand resulting from population growth and shifts in dietary preferences (Mølgaard Lehmann et al., 2020). This necessitates a more comprehensive evaluation of food production systems that focuses not only on the quality and quantity of yields but also on the delivery of ecosystem services, including biodiversity preservation, carbon sequestration, soil fertility, and nutrient cycling.

Agroforestry is considered as one of the most powerful tools to mitigate and adapt to climate change in the agricultural sector and described by the Food and Agriculture Organization (FOA) of the United Nations as "*Agroforestry is a collective name for land-use systems and technologies where woody perennials are deliberately used on the same land-management units as agricultural crops and/or animals*" (FAO, 2015). It can be considered a nature-based solution in the battle against climate change through the integration of nature into agriculture and can provide multiple ecosystem services (Hernández-Morcillo, 2018). Agroforestry shows great potential to harbour biodiversity, sequester carbon, decline soil erosion and runoff control, as well as improve nutrient and water cycling (Castle et al., 2022).

Biodiversity

Agroforestry is recognised as an important player for reducing species loss in agricultural landscapes (Santos et al., 2022). Agricultural intensification in general and deforestation in tropical regions are significant drivers of biodiversity loss, which in turn affect ecosystem functions. One concrete example of this is the impact of the domestication of crops derived from wild variants, which has resulted in a direct reduction of plant diversity. While modern agriculture is largely blamed for global biodiversity loss, it has potential to support biodiversity provided improved management techniques (Udawatta, Rankoth & Jose, 2019). Through the inclusion of nature into agriculture, agroforestry can provide habitat, germplasm for sensitive and protected species, improve connectivity by acting as corridors, and help conserve biodiversity through improved regulatory ecosystem services that will be addressed hereunder.

Carbon sequestration

Arguably the most important role of agroforestry in mitigating the effects of global climate change is its potential to lower CO_2 emissions by sequestering carbon from the atmosphere (Torralba, 2016). Three main pathways of carbon sequestration by agroforestry through which it can help reduce atmospheric carbon are conservation of current carbon pools through prevention of further deforestation; carbon sequestration achieved through enhanced agricultural systems; and substitution by establishing biofuel and bioenergy plantations to replace the use of fossil fuels. Through these processes, improved agricultural systems can act as carbon sinks, rather than sources (Kay et al., 2019).

The aim of this review is to provide a comprehensive overview of the extent to which agroforestry contributes to the enhancement of ecosystem services offered by agricultural systems in temperate climate zones. To do so, the following topics will be discussed:

1. *How do ecosystem services provided by agroforestry in temperate zones compare to those of conventional agriculture, and how to planting density and age stand in relation these services?*
2. *What is the potential of agroforestry in temperate regions to mitigate the effects of climate change?*

Through answering these questions, the potential of agroforestry to conserve or restore ecosystem services that have been affected by modern agricultural practices will be assessed, with implications for climate change mitigation capabilities, thereby informing future research, policy development, and land management practices. By employing rigorous and transparent methodologies, we aim to provide an evidence-based foundation for decision-making in the field of agroforestry and ecosystem services enhancement.

Methods

In this section, a comprehensive overview of the methodological approach used in the conducted systematic review on the extent to which agroforestry practices contribute to the enhancement of ecosystem services is provided. Following the guidelines in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al., 2009) protocol, transparency, rigor, and reproducibility in the used methodology is ensured. This formalized, evidence-based approach was initially developed in the realm of health sciences. However, more recently they have garnered attention in conservation and environmental management, serving as valuable guides for research and policy development. The adoption of this structured methodology for a literature review offers advantages rooted in its rigorous and objective nature, aligning with the fundamental principles of impartiality and transparency. The systematic review approach aims to construct fresh insights though an examination of existing research findings. In this review, a pure literature review will be conducted without further meta-analysis. Its purpose is to provide an overview of recent findings on developments in the field of agroforestry, with a focus on soil organic carbon (SOC), and biodiversity.

Search strategy

To identify relevant studies for inclusion in this review, a comprehensive search across academic databases, Web of Science (WOS) and Scopus, was conducted. The formulated search strategy incorporated broad search terms that include overarching themes and synonyms relevant to agroforestry to capture a broader range of relevant articles. Terms and synonyms are combined using Boolean Operators (AND, OR) to create search strings. In the search strategy, three search strings were combined to yield the preferred information with the following topics: carbon sequestration, biodiversity, and nutrient cycling.

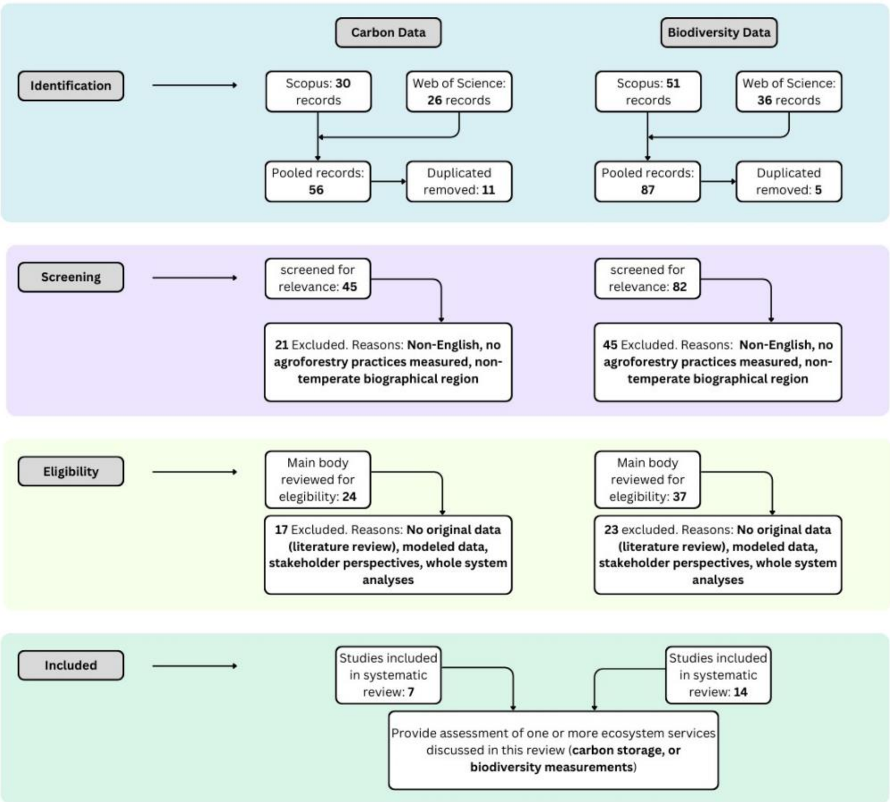

Figure 1 Flowchart of the search strategy used for this literature review. Included are the number of records found, and exclusion criteria for the data selection.

Related definitions describing the aforementioned queries were included. All search strings were related to agroforestry and its equivalent describers, and Europe and/or temperate climate zones. Additionally, shorter variants of on topic terms were used to include different variants of the word.

String searches used were identical or a variation of the following two examples:

- Carbon data: “carbon sequestration AND carbon storage AND agroforest* OR silvopast* OR silvoarable OR hedgerow* AND europ*”
- Biodiversity data: “biodiversity AND conservation AND agroforest* OR silvopast* OR silvoarable OR hedgerow* AND europ*”

To ensure the comprehensiveness of the search, I utilized search strings in an iterative manner by adapting and changing search queries when I noticed it needed alterations or additional terms. To focus the review on recent literature, and through that maintain relevance, I limited my search to articles published from January 1, 2018, up to the most recent available data. To uphold the quality and reliability of the study, only peer reviewed articles are included. While a wide variety of search terms were used to retrieve information as reliably as possible, it is likely that some relevant publications are not captured in the data search.

After conducting the searches, the results were exported from WOS and Scopus into an Excel sheet. This document served as a repository for all retrieved articles, to make the final selection simpler. The data from both sources were then merged and duplicates were eliminated, ensuring that each unique study was represented only once. Searches performed for this review took place in October 2023 have resulted in the final search string retrieving a collective number of 62 total records from WOS and a total of 77 records from Scopus adding up to a total of 139 records. From these, studies were manually selected and excluded in the following manner:

1. Addresses one or more agroforestry practices withing the European biogeographical region, or other temperate climatic zones.
2. Provide assessment of one or more ecosystem services discussed in this review (carbon sequestration, or biodiversity).
3. Publications without original data (e.g., literature reviews) and modelled data
4. Non-English and Non-Dutch records are removed.

To do so, inclusion criteria were applied to the title, then to the abstract or equivalent, and the remainder by viewing items (such as figures and tables) at full context.

Results

Carbon data

Data retrieved from the literature review indicates an overall positive effect of agroforestry practices on underground carbon storage. In the found studies, mainly spatial comparisons were made, with some additional temporal analyses. From the papers included into the analyses, the conducted experiments all conducted comparisons of carbon stocks or carbon sequestration rates between an agroforestry system and a conventionally managed agricultural system. Comparisons were made either spatially (direct comparisons between location) or temporal (comparisons over time). From our gathered results, these comparisons were conducted in silvopastoral systems, hedgerows, farms using interplanting methods, hedgerows, short rotation coppices, and windbreaks.

In Bateni et al. (2021), a comparison of soil C stock was made between different land-use practices of which the most relevant to this study is the comparison of the measurements in silvopastoral systems consisting of low-density olive groves (135 trees ha^{-1}) and pastures, and in high density conventionally managed olive groves (400 trees ha^{-1}). Here they found carbon stocks in the upper 30 centimetres in silvopastoral fields (50 ± 4 Mg C ha^{-1}) comparable to their measurements in conventionally managed groves, namely 47 ± 2 Mg C ha^{-1}. Higher values, however, have been recorded in the wooded (more bewildered) areas of the silvopastoral fields (71 ± 9 Mg C ha^{-1}). Interestingly, taking tree density into account, it can be noticed that while the two systems have carbons stocks of similar magnitudes, the silvopastoral system has a much lower tree density than the conventional olive grove. Similar comparisons were made by Jha (2018), where they compared two poplar (*Populus euramericana*) plantations, one with an intercropping agroforestry (poplar-wheat intercropping) system, and the other a monoculture. On a hectare basis they found a pattern similar to Bateni et al. (2021) for soil carbon stocks where they found carbon storage of 330 Mg ha^{-1} for their agroforestry system, whereas they found 304 Mg ha^{-1} carbon storage for monoculture counterpart. Similar to the tree planting densities in Bateni et al. (2021), tree density reported by Jha (2018) was lower for their agroforestry system (139 trees ha^{-1}) than their monoculture system (204 trees ha^{-1}). Their finding might be counterintuitive as one may expect higher soil carbon pools with increased tree density, however, neither studies found such relationships. On the contrary, they found similar or even higher carbon pools for lower tree densities, indicating that these agroforestry systems are more efficient at fixating carbon in the soil than monoculture plantations.

Additionally, Kanzler et al. (2021) compared the performance of short rotation coppices and adjacent hedgerows to measurements taken in a conventional short rotation alley cropping system. They observed higher values for soil organic carbon (SOC) stocks in the hedgerows and short rotation coppices, 5.0 and 5.8 Mg ha^{-1}, as compared to the alley cropping measurements (2.3 Mg ha^{-1}). SOC accumulation in the litter layer of the measured hedgerows was superior to those of the short rotation coppices or the alley cropping systems, indicating a steady supply of organic material derived from trees. Wiesmeier et al. (2018) also compared the efficiency to store carbon, of land under different management types. Here they compared carbon stocks found in natural grasslands to those found in windbreaks, cropland conventional, cropland with manure application, and cropland with cover cropping. Natural grasslands outperformed all the land management types with 177.1 ± 38.7 Mg C ha^{-1} in the top 30 cm of soil. However, second best performing land type was windbreaks, with SOC stocks of 145.7 ± 24.9 Mg C ha^{-1} in the top 30 cm of soil, and relatively high sequestration rates of 0.9 Mg ha^{-1} yr^{-1}.

In Biffi et al. (2022), both temporal and spatial evaluations are made. They compared carbon stocks under hedgerows of different ages, through which they made calculations to determine carbon sequestration potentials through time. Here they found that older hedgerow systems have higher below ground carbon stocks than younger systems. Analysing hedgerow systems of different age, namely systems that were 2-4, 10, 37, or 40+ years old, they found that SOC stock beneath hedgerows increased relative to the adjacent field with hedgerow age. While sequestration rates increased with age, it did not do so linearly. Over time, the rapid increase in sequestration potential flattens out, respectively to the age classes they measured SOC values in the top 30cm of soil of on average 6.8, 18.2, 41, and 42,3 Mg C ha^{-1}. With these numbers they indicate that the capacity of soils to sequester carbon is finite and will reach an equilibrium over time, and thus will not continue to sequester carbon indefinitely. This highlights the importance of not only establishing new agroforestry systems, but also to maintain those that have already reached equilibrium to keep sequestered carbon fixed in the soil.

Similarly, Black et al. (2023) compared hedgerow systems under different creation and management types, where they found that variety in carbon stocks are highly dependent on a large number of factors, including age, management regime, hedgerow width and height, species, and structure (Black et al., 2023). They found that lower intensity management, and broader width of hedgerows resulted in overall higher carbon stocks than when they are trimmed back to the minimum allowable width in areas qualifying for farm payments. Additionally, Van Den Berge et al. (2021) studied the effects of hedgerows and 'ghost' hedgerows on the SOC stocks in arable fields. With 'ghost hedgerows', they refer to sites where hedgerows have been removed, but the original position of it is still visible in the landscape. Comparing the measurements of the hedgerows and 'ghost' hedgerows to samples taken in grass strips, they found that SOC stocks were significantly higher in hedgerows (81.7 ± 28.8 Mg C ha^{-1}) than in 'ghost' hedgerows (57.9 ± 14.1 Mg C ha^{-1}), while SOC stocks were not significantly different between ghost hedgerows and grass strips (6.6 ± 14.5 Mg C ha^{-1}). For all measurements changes in the SOC concentration decreased with a larger distance from the field margin, of which the decrease for the hedgerows is significantly larger. Ghost hedgerows show little to no traces of the built-up SOC stocks resulting in a lost carbon sequestration potential of almost 5000 Mg C in the top 23 cm of the soils in their 5600 ha study area (Van Den Berge et al., 2021). The relevance in making comparisons between agroforestry management types lay in its potential to highlight key attributes that make agroforestry (more) successful. Here the importance of age, management intensity, and removal emphasize the need for a nuanced understanding of how we can enhance and promote sustainable land management practices.

__Table 1__ Systematic overview of the results obtained from the literature review for carbon data. From left to right, it is indicated whether in the analysed paper they investigated C stocks or sequestration. Effects shows whether a positive effect of agroforestry (AF) was found. It is also indicated whether comparisons in the literature were temporal (over time) or spatial (direct comparisons between places). Kanzler, Böhm & Freese (2021) investigated 2 AF types indicated with (A) for their short rotation coppice measurements, and (B) for their hedgerow measurements.

Carbon stock/ carbon sequestration	Effect	Sampling depth (cm)	Range	Unit	Temporal/spatial	AF type	Source
Carbon stock	+	0-30	50 ± 4 (forested) 71 ± 9	Mg C ha^{-1}	Spatial	Silvopastoral	Bateni et al., 2021
		30-60:	13 ± 1 (forested) 17 ± 1				
Carbon stock	+	0-30	111.2 ± 12.9	Mg C ha^{-1}	Temporal and spatial	Hedgerow	Biffi et al., 2022
		0-50	158.4 ± 19.1				
Carbon sequestration			1.48	Mg C ha^{-1} $year^{-1}$			
Carbon stock	±	0-100 (regular)	38.9 ± 21.5	Mg C ha^{-1}	Temporal and spatial	Hedgerow	Black et al., 2023
		0-100 (irregular)	24.8 ± 18.8				
Carbon stock	+	250-300	330	Mg C ha^{-1}	Spatial	Interplanting	Jha, 2018
Carbon stock	+	0-3 (top soil)	(A): 5.8 (B): 5.0	Mg C ha^{-1}	Spatial	(A) Short rotation coppice & (B) Hedgerow	Kanzler, Böhm & Freese, 2021
Carbon sequestration	+		(A): 0.43 (B): 0.37	Mg C ha^{-1} $year^{-1}$	Temporal		
Carbon stock	+	0-23	81.7 ± 28.8	Mg C ha^{-1}	Spatial	Hedgerow	Van den Berge et al., 2021
Carbon stock	+	0-10	51.4 ± 9.5	Mg C ha^{-1}	Spatial	Windbreak	Wiesmeier et al., 2018
		10-30	94.3 ± 15.5				
		0-30	145.7 ± 24.9				
		0-30	0.9	Mg C ha^{-1} $year^{-1}$	Temporal		

Biodiversity data

Overall, a positive effect of agroforestry methods on all three analysed phyla was found. For phylum "Chordata", measurements for birds, mammals, and amphibians and lizards were analysed. In the classification for birds, Rösch et al. (2019) reported findings on the responses of birds (predator) and grasshoppers (prey) to newly created wood pastures. They compared observed species richness and densities to those of open wood pastures and forests. They found that wood pastures are exceptionally effective at harbouring a high species richness in both birds, and grasshoppers. Bird species richness was higher in wood pastures in comparison to forests. Contrary to expectations by the authors, the number of breeding pairs in wood pastures was of similar levels as those in forests, confirming the positive effects of agroforestry systems on bird diversity. Another important aspect they found is that the wood pastures were home to a high number of red-listed bird species, more so than in forests were hardly any red-listed species were found. This indicated the potential of wood pastures in the conservation of endangered bird species, such as the nightjar, woodcock, and tree pipit.

Similar findings were made for mammals, in particular bats (Froidevaux et al., 2019) and badgers (Pita et al., 2020), where they found that lower management intensities, and higher hedgerow densities increase the number of individuals observed. Froidevaux et al. (2019) found strong positive relationships between trimming regimes that affected hedgerow heigh which directly and indirectly influenced bat occurrence, where bat species richness significantly increased with time since last trimming possibly as a result of increased prey abundance. Pita et al. (2020) also analysed habitat interference, however they looked at the density of paved road and found that badger populations in intensively used farmland are vulnerable to road infrastructure. Occupancy rated decrease significantly with increased paved road densities, possibly attributed to relative high number of roadkill records. The implementation of agroforestry settings that are minimally managed and thus have low interference levels would increase badger occupancy rates. These findings are in accordance with those for amphibians and lizards (Boissinot et al., (2019); Fernandes et al., (2019); Guiller et al., (2022)). Here, all three found higher occurrences for their measured species in their respective agroforestry method compared to conventional farmland. They also found decreasing numbers of species richness and individual occurrences as an effect of habitat interference, such as grazing intensity, road density, and human activity. All indicate that agroforestry systems are effective at providing habitat for species that would otherwise be scarce or absent in open farmland landscapes. In some cases, agroforestry systems even harbour endangered species that would not be found in natural systems of higher successional stages.

Arthropoda abundance and species richness is mainly approached from a multifunctionality perspective, namely pollination and biocontrol potential. Benoit et al. (2019) made a comprehensive analysis of several pollinating, predatory, and pest species. They found that understorey vegetation strips are home to a wide range of overwintering invertebrates, as opposed to conventional crop alleys. They found that pest species had a preference for overwintering in crop vegetation, while beneficial species overwintered predominantly in the vegetation strips. This indicates the beneficial effects of agroforestry practices in combination with, or nearby, agricultural fields as natural biocontrol will take place in larger degrees, diminishing the need for pesticides (Mestre et al., 2018). The presence of rich invertebrate communities in such strips could also benefit species in higher taxa, such as birds, mammals, and lizards, as recorded in Rösch et al. (2019). They found that surprisingly, due to their high microclimatic demands, the investigated wood pastures were home to a high diversity of grasshoppers, a prey to many avian species. Froidevaux et al. (2018) support these findings through the high abundance of insect prey in hedgerows off which the researched bat species feed. Strong beneficial effects of agroforestry measures have been found not only in pest control potential, but also in insect pollination by Sutter et al. (2017), and Couthouis et al. (2022), who found higher rates for pollination (expressed in pollinator presence), and pest control as an effect of nearby hedgerows and wildflower strips adjacent to conventional agricultural fields. All findings agree that semi-natural habitats in agroforestry practices at the local scale contribute to enhancing ecosystem multifunctionality, owing to their importance for biodiversity conservation and associated ecological functions as compared to agricultural fields.

Analysing data on the biodiversity effects of agroforestry provides evidence for its beneficial effects not only on animals and insects, but also on vegetation. Research by Vanneste et al. (2020a;2020b) found that linear features, such as hedgerows, have high potential to serve as valuable secondary habitats or even potential seed dispersal routes for isolated habitat fragments. This holds true not only at regional scales but also at a continental extent. They (Vanneste et al., 2020b) found that forest specialist herbs are likely to colonise hedgerows when attached to a forest patch, and then gradually migrate along the hedgerow, that now serves as a corridor, through successive generations. Research by Lucie et al. (2023) found that an increased density of hedgerows in an area lead to an increased productivity of adjacent grasslands. They demonstrated plant trait mediated effects of landscape heterogeneity on plant productivity and temporal stability of grasslands. With this Lucie et al. (2023) indicate the importance of land management through the conservation of hedgerows to help maintain robust and resilient productivity of grasslands attributed to the positive impact these hedgerows have on plant functional diversity. Findings by Fredehas et al. (2022) further support these findings by looking at below ground biodiversity effects of hedgerows. They found that planting hedgerows contributes to belowground AMF diversity. Hedgerows demonstrate efficiency in offering habitat to AMF, thereby contributing to the preservation of landscapes characterized by high soil biodiversity.

***Table 2** Systematic overview of the results obtained from the literature review for the biodiversity data. From left to right, it is indicated which phylum was investigated. In classification it is indicated which overlapping group is analysed after which they were further specified under measured species. Effects shows whether a positive effect of agroforestry (AF) was found. It is also indicated whether comparisons in the literature were temporal (over time) or spatial (direct comparisons between places).*

Phylum	Classification	Measured species	Effect	Temporal/spatial	AF type	source
Chordata	Birds	Various birds[11]	+	spatial	Wood pastures	Rösch et al., (2019)[11]
	mammals	Various bats[5], Badgers[10]	+	spatial	Hedgerows[5,10]	Froidevaux et al., (2019)[5]; Pita et al., (2020)[10]
	Amphibians and reptiles	Various[2], Psammodromus algirus[4], Vipera berus[7], Lancerta Bilineata[7]	+	Spatial	Hedgerows[2,7], montado[4]	Boissinot et al., (2019)[2]; Fernandes et al., (2019)[4]; Guiller et al., (2022)[7]
Arthropoda	Predatory insects	Carabids[1,3,12], Coccinellidae[1,3], Formicidae[1], Arachnida (spiders)[3,9],	+	Spatial	Understorey vegetation strips[1,12], alley cropping[1], hedgerows[3,9,12], treelines[9]	Benoit et al., (2019)[1]; Couthouis et al., (2022)[3]; Mestre et al., (2018)[9]; Sutter et al., (2017)[12]
	Pollinators	Honey bees[3,12], Butterflies[3], various Diptera[3] Syrphidae[1,3,12],	+	Spatial	Hedgerows[3,12], Understorey vegetation strips[1,12]	Benoit et al., (2019)[1]; Couthouis et al., (2022)[3]; Sutter et al., (2017)[12]
	Other	Slugs[1], Snails[1], Aphidae[1,3], Elateridae[1], Staphylinidae[1,3], Moths[5], Grasshoppers[11]	±	Spatial	Alley cropping[1], Hedgerows[3]	Benoit et al., (2019)[1]; Couthouis et al., (2022)[3]; Froidevaux et al., (2019)[5]; Rösch et al., (2019)[11]
Plantae	Herbaceous vegetation	Grassland[8], understorey growth[13,14]	+	Spatial	Hedgerow[8,13]	Lucie et al., (2023)[8]; Vanneste et al., (2020a)[13]; Vanneste et al., (2020b)[14]
	Arbuscular mycorrhizal fungus	N.A.	+	Spatial	Hedgerows[6]	Gonzáles et al., (2022)[6]

Discussion

Carbon pools and sequestration

Data found in the literature review provides an overwhelmingly positive effect of agroforestry on local carbon storage and biodiversity. The authors demonstrate a high potential to store and sequester carbon, which could play a crucial role mitigating the effects of climate change.

Agroforestry systems act as carbon sinks, absorbing atmospheric carbon dioxide and storing it in their above- and belowground biomass. As a result, incorporating agroforestry practices into current conventional agriculture could enable a more sustainable land-use strategy that aligns with climate change mitigation goals. To further support the findings from this review, Drexler et al. (2021) performed a meta-analysis which adds important statistical significance to results that coincide with those of this review. They compared carbon stocks and carbon sequestration rates in the soil under hedgerows and mono cropping systems and natural grasslands. Only direct comparisons were made, including data found through a literature review, and their own data. They provide an overwhelmingly positive effect of hedgerows on carbon storage and sequestration, coinciding with results obtained from our own review. They, however, found no significant differences between SOC stocks in grasslands and under hedgerows. Hence, hedgerows, in terms of carbon storage, perform similarly to natural systems indicating its relevance in incorporating them into an agricultural setting. The higher C sequestration values found under hedgerows compared to mono cropping systems may be explained by the generally higher SOC deficit of cropland soils. This deficit allows the perennial structures of hedgerows to result in a more efficient retention of C by hedgerows leading to higher SOC sequestration rates (Mayer et al., 2022). Moreover, hedgerows and windbreaks are often established to prevent wind and water erosion, which may lead to the deposition of organic carbon-rich materials and sediments.

Reference	***SOC Control***	***SOC Hedgerow***	***SOC unit***	***Sampling depth [cm]***	***n (sites)***
Cropland Control					
Baah-Acheamfour et al. 2014	53.1	65.2	g kg^{-1}	10	12
Dhillon & Van Rees 2017	73.7	79.5	Mg ha^{-1}	50	10
Holden et al. 2019_a	19.0	31.0	g kg^{-1}	7	3
Monokrousos et al. 2006_a	12.9	9.6	g kg^{-1}	10	1
Monokrousos et al. 2006_b	15.2	28.0	g kg^{-1}	10	1
Paulsen & Bauer 2008_a	98.0	163.0	Mg ha^{-1}	60	1
Thiel et al. 2015_a	80.8	106.5	Mg ha^{-1}	40	4
Thiel et al. 2015_b	72.9	76.7	Mg ha^{-1}	40	4
Van Vooren et al. 2018_c	32.3	45.5	Mg ha^{-1}	20	1
Van Vooren et al. 2018_d	40.5	46.1	Mg ha^{-1}	20	1

Figure 2 From Drexler et al. (2021). This table shows results yielded by the meta-analysis performed by Drexler et al. (2021). Here we see the average values for SOC found under hedgerows and in their monocropping controls.

Another interesting finding is that not only do agroforestry system support higher carbon fixation in the soil, but it does so at lower planting densities. As discussed in the results section, research by Bateni et al. (2021) and Jha (2018) show equal or higher SOC pools in their respective agroforestry systems as compared to their monoculture control measurements. Attributing their findings to different causes. Bateni et al. (2021) speculate that the difference in SOC pools, despite the lower tree density, is a result of the accumulation of leaf litter on the surface, and management practices such as tillage. Residues from olive oil production and pruning wood are usually removed under the intensive management practices of monoculture plantations, resulting in a general loss of C from the system (Bateni et al., 2021). To add to this theory, Jha (2018) argues that the key component for long-term C storage in the soil may be the tree roots. Jha (2018) hypothesizes that the interaction of dead tree roots and the water table plays an important role. In saturated horizons, the decomposition of organic matter is extremely slow, leading to a more effective long-term C storage. As the total system of tree roots are suspended in a large volume of soil, it is difficult to make direct measurements of SOC as a large chunk of for example fine- or deep shooting roots will be overlooked. Hence, measurements at deeper sampling depths are needed to map the total C storage potential, especially those of agroforestry trees as they have deeper roots when comparing them to monoculture trees (Jha, 2018). Also notable to mention is wood density, as measured by Jha (2018) differed considerably between the agroforestry and monoculture measurements. Agroforestry trees produces 13% more wood volume and 10% more biomass than its monoculture counterparts of the same species. This means that individual trees in agroforestry systems could grow larger and have a denser wood volume than those in monoculture plantations. Jha (2018) ascribes this effect to a lower inter tree competition for resources, like light, as they have more growing space in the agroforestry systems.

Conversely, the removal of agroforestry systems through the years have been a potential carbon source. Hence, it is important to consider that the gain in SOC is reversible. Research van Van Den Berge et al. (2021) in the countryside of Turnhout, Belgium, show a decline in percentage of hedgerows of 74% from 1960 to 2016, creating a large number of what they call 'ghost' hedgerows. The usage of hedgerows is one of the oldest, yet actively declining, forms of agroforestry in Europe. They assessed SOC stocks in arable fields situated adjacent to hedgerows, remnants of 'ghost' hedgerows, and grass strips to investigate the impact of hedgerow trees on SOC stocks and to assess the residual presence of SOC following the removal of hedgerows. In agreement with previously discussed literature, they found a positive effect of hedgerows on SOC stocks. However, investigating the legacy effects of these agroforestry systems, they found that built up SOC stocks were almost completely diminished over a period of maximally 59 years, and minimally 24 years (Berge et al., 2021). Because of this, it is not only important to restore degraded ecosystems through the use of agroforestry practices, but also to preserve what is left of it to keep stored carbon in the ground. The implementation of a stringent policy for agroforestry conservation would prove to be a highly efficient measure for mitigating climate change in agricultural landscapes.

While it may seem obvious that SOC stocks under hedgerow systems are higher than in monocropping systems due to their dense and diverse nature, it is important to note that the purpose of agroforestry is not strictly to replace conventional agriculture but rather for it to be an addition to it. As regions dominated by cropland experience more environmental pressures than grasslands, the establishment of for example hedgerows is likely to achieve the best synergies with ecosystem functions, such as carbon storage but also biodiversity (Kay et al., 2019). Based on their calculations, they found that establishing hedgerows on former cropland in the temperate climate zones could result in soil organic carbon stock increases by 32±23% on average (Drexler, Gensior & Don, 2021). Similar values have been found by research by Van Vooren et al. (2017) with 22%, and Cardinael et al. (2018) with a relative increase of 21%. It is thus important to consider that not one single solution fits all agricultural setting. A mosaic of various agroforestry practices that are implemented on land currently used for monoculture plantations would create a diverse environment with a larger variety of tree and plant species. This diversity would provide habitat for a wide range of flora and fauna, allowing for the preservation of multiple ecological niches while mitigating the emissions of agricultural practices. A practical approach to successfully implement this would be to, for example, establish silvopastoral systems in cattle-occupied fields, or establish hedgerows around monocultural plots. This multifaceted agricultural strategy would not only promote ecological diversity, but also minimize potential financial losses for farmers.

Biodiversity

Agroforestry systems do not only support carbon storage, but also harbour high biodiversity contributing to the conservation of various (red-listed and specialist) plant and animal species (Rösch et al., 2019; Vanneste et al., 2020). Agroforestry systems offer diverse landscapes and structured habitats, incorporating both open agricultural lands, and wooded (multi-layered) elements. This heterogeneity attracts a variety of species, providing habitat niches for flora and fauna that may not thrive under the conditions of conventional agriculture. Trees and the bushy layers of agroforestry systems can even act as microhabitats (Fernandes et al., 2019), offering nesting sited (Boissinot et al., 2019), shelter, and foraging areas (Guiller et al., 2022; Kay et al., 2019) for a multitude of species. Additionally, the presence of these semi-natural structures in agroforestry creates ecological corridors that enhance connectivity between isolated natural areas (Hernández-Morcillo et al., 2018). This enhanced connectivity facilitates the movement and dispersal capabilities of species, supporting geneflow and thus reducing the risk of isolation for populations. This is in agreement with research by Mullins et al. (2014) who assessed the connectivity of Natura2000 sites in a western Mediterranean region. They used the wood mouse as a focal species and obtained genetic data for 393 species that were distributed between two Natura2000 sites. They found that the genetic diversity for this generalist species was high, and no significant differences between the two populations exist (Mullins et al., 2014). This successful genetic flow was mainly attributed to the abundant Montado systems between the natural sites, indicating the importance of these agroforestry ecosystems to maintain connectivity between natural ecosystems. In the face of global challenges such as climate change, such genetic exchanges are crucial to the overall genetic diversity of flora and fauna, enabling species to adapt to changing environmental conditions. As a result, agroforestry contributes to the resilience of plant and animal species by acting as reservoirs of genetic resources providing a diverse array of plant and animal species that can serve as germplasm for sensitive and endangered species.

Multifunctionality: pollination and pest control

This increased biodiversity potential comes with an increase in ecosystem multifunctionality, providing a range of ecosystem services that extend beyond conventional agriculture. In particular, this multifunctionality extends to pollination and pest control, two critical services wherein agroforestry excels, showcasing the intricate relationship between these systems and their ecological functionality. With their diverse vegetation, agroforestry landscapes attract a wide variety of pollinators, including bees, butterflies, hoverflies, and other insects (Benoit et al., 2019; Couthouis et al., 2022). The presence of flowering trees, shrubs and herbaceous vegetation in agroforestry creates a rich and semi-continuous source of nectar and pollen. This abundance and diversity of resources enhance pollination efficiency, as pollinators can move freely between crops and wild vegetation, leading to an increased fruit set, improved seed production, and possibly better crop yields. This is an especially important consideration for crops that rely on insect-mediated pollination, which is the case for many fruit bearing crops. This exact effect is what research by Varah et al. (2020) and Kay et al., (2019) sought to investigate. Varah et al. (2020) assessed whether agroforestry can provide increased pollination services compared to monocropping systems. In their study, they investigated six UK sites, each containing an agroforestry and monocropping system over a span of three years. As a proxy for pollination success, they used pollinator abundance and diversity, as well as seed set. Their results show that agroforestry treatments indeed provide greater pollination services than monocultures. They identified twice as many solitary bees and hoverflies, and 4.5 times more seed set in agroforestry systems compared to monocropping treatments. Additionally, species richness of solitary bee species was on average 10.5 times higher in agroforestry systems. This effect could be attributed to findings by Kay et al. (2019) who found that in total there was a higher proportion of flowering and nesting resources for solitary bees in their agroforestry treatments.

Pest control is an issue agricultural systems have been struggling with likely since the domestication of crops. The use of pesticides has had an immense impact on our direct environment and food chains (Geiger et al., 2010). One way to decrease the amount of pesticides needed is through the application of natural predation. The structural complexity of agroforestry systems not only attract pollinators, but also natural predators such as birds, bats, and beneficial insects (Rösch et al., 2019; Pita et al., 2020). These predators could play an important role in controlling pest populations by preying on insects that are harmful to crops. Through integrating these semi-natural landscapes into agriculture, biological pest control mechanisms where natural enemies of crop pests are more efficient than in monoculture cropping fields and can therefore contribute to pest suppression (Boinot et al., 2019). This will result in a reduces reliance on chemical pesticides, promoting environmentally friendly and sustainable pest management practices. Boinot et al. (2019) also found that crop pests predominantly overwintered in crops, while predators overwintered in the vegetation strips. When suitable overwintering habitats for predators are missing, it could lead to higher probability of pest outbreaks. Additionally, edge-effects are frequently observed to result in decreased predator abundance and diversity in the field core. Hence, more research is needed on the dispersal of a wide range of invertebrates in the presence of agroforestry systems. Because of this, Boinot et al. (2019) suggest understorey (non-crop herbaceous) vegetation strips as undisturbed habitats within agroforestry fields themselves to enhance spillover of beneficial invertebrates to the core of these fields.

A meta-analysis by Pumarino et al. (2015) supports the findings by Boinot et al. (2019) through their results. They found that weeds were less abundant and natural enemies to crop pests were more abundant in agroforestry systems. The potential for agroforestry to function as corridors, such as hedgerows and buffer strips, further enhances this biological pest control effect. Beneficial insects can freely move throughout the landscape, which facilitates the dispersal of natural enemies to areas where pest populations are high (Mullins et al., 2014), enhancing the overall effectiveness of biological pest control. However, it should be noted that the effect size found differs between different research findings. For example, Kranz et al. (2018) investigated the impact of shrub crops on the biological control on tree crops in an interplanting system. Their results suggest that shrub cover interplanting does not inherently lead to positive pest control effects. This indicates a high variability in effectiveness of different agroforestry systems to enhance natural predation in agriculture, calling for a need to have these differences mapped.

Concluding remarks

The combined effects of agroforestry on ecosystem services, encompassing carbon storage, increased biodiversity, and ecosystem services such as pollination and pest control, contributes to the overall resilience of agroforestry crops. By fostering biodiversity and ecological balance, agroforestry demonstrates its potential to enhance crop productivity while minimising environmental impact and positions itself as a multifaceted land-use strategy (Boinot et al., 2019). Enhanced productivity and resilience are especially important in the face of current environmental challenges, such as climate change and the loss of biodiversity. By contributing to climate mitigation and fostering biodiversity conservation, agroforestry demonstrates a high potential to harmonize agricultural productivity with the needed environmental stewardship.

Methodological inconsistency

While this review shows a great potential for agroforestry to play an important role in mitigating the effects of climate change, it is important to acknowledge the diversity in methodologies and parameters across the available data (Lucie er al., 2023). This may lead to inconsistencies and make direct comparisons of data challenging. For example, spatial and temporal variations, as well as differences in land-use practices, management techniques, and measurement depths could contribute to discrepancies in the reported carbon stocks. For biodiversity, there is little to no overlap between measured species. It may not be fair to extrapolate positive findings for one species, to another, as its inner workings and ecosystem niche may be incomparable. These findings may be a direct result from the scarce recent literature (Drexler et al., 2021), especially on the effects of agroforestry practices in temperate regions as literature was more abundant on tropical ecosystems. Hence, more research should be done on the matter at hand in general.

Standardization of data collection methods and metrics would enhance the comparability of findings in future studies. This standardization of measurement protocols is crucial for ensuring consistency, and comparability across diverse agroforestry studies. Establishing guidelines for data collection, including sample depths, measurement techniques, reporting units, and measured species, could enhance reliability of measurements on the benefits of agroforestry practices. This standardization will facilitate meta-analyses for reviews and allow researchers to draw more robust conclusions about the impacts of agroforestry on ecosystem services.

Along with the need for more standardized measurement, comes the need for more temporal data. Conducting long-term studies is imperative to capture the dynamics withing agroforestry systems over time. For example, short-term studies may not fully represent the system's capacity to store and sequester carbon over time, or its potential to harbour keystone species that enhance ecosystem resilience. Studies spanning multiple years or even decades can provide more robust insight into the trajectory of carbon accumulation and biodiversity potential, helping identify trends, potential saturation points, and the sustainability of agroforestry practices in maintaining or enhancing ecosystem services.

Additionally, future research should adopt a multifactorial analysis approach to explore the interaction between the various components influencing ecosystem services provided by agroforestry (Sutter et al., 2017). Considering factors such as hedgerow width, height, species composition, and management practices will help identify the most influential variables (Froidevaux et al., 2019). A nuanced understanding is essential for tailoring agroforestry strategies to maximise their potential in mitigating the effects of global climate change, based on specific environmental conditions and management goals. This will guide the development of adaptive management, and an increased nature inclusivity that promote the long-term sustainable land-management practices, balancing ecological conservation and health with human needs.

Conclusion

The aim of this literature review was to provide a comprehensive overview of the extent to which agroforestry contributed to the enhancement of ecosystem services offered by agricultural systems in temperate climatic zones. With this, we hoped to gain further insights into the current knowledge gap on how and if agroforestry practices have the potential to conserve or restore ecosystems affected by modern agricultural practices. Our analysis has shown that literature on agroforestry overwhelmingly supports the beneficial effects of agroforestry on both carbon storage and biodiversity. The demonstrated potential of agroforestry practices to store and sequester carbon positions agroforestry as a crucial approach in mitigating the effects of climate change. A commonly debated effect of agricultural intensification and climate change is their effect on biodiversity, or rather the decrease thereof. From this review we can conclude that agroforestry has potential to play an important role in biodiversity conservation. These diverse agro-ecological landscapes attract and support a large variety of plant and animal species. Strategically constructing agroforestry systems makes it such that they are effective at functioning as ecological corridors that enhance connectivity between natural areas, supporting species dispersal and geneflow. Pollination, and pest control are important ecosystem services that agroforestry practices support. The structural complexity of agroforestry systems supports pollinators and natural predators, promoting biological pest control and pollination efficiency. This in turn may lead to increased crop yields, and a reduced dependency on chemical pesticides.

While research is now showing promising results on the positive effects of agroforestry on our environment, (consistent) data remains relatively scarce. Focus should be laid on standardising measuring protocols to create more easily comparable data. Additionally, conducting long-term studies is imperative to capture the dynamics withing agroforestry systems over time. A multifactorial analysis approach should be adopted to explore the interaction between the various components influencing ecosystem services provided by agroforestry.

In conclusion, the combined effects of agroforestry on ecosystem services such as carbon storage and biodiversity contribute to the resilience of agroforestry crops. The large diversity of flora and fauna enables adaptation to a changing environment, which now more than ever, is important in the face of global climate change. This multifaceted land-use strategy demonstrates its potential to enhance crop productivity while taking climate mitigation into consideration. Hence, agroforestry as an addition to conventional monocropping systems stands out as a harmonious solution, aligning with agricultural productivity and ecological conservation through nature inclusivity.

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