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Agroforestry: an agroecological practice in the light of Ecological Economics

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Abstract: The purpose of this study is to contribute to the comprehension of the relationship between the concepts of agroforestry, agroecology, and ecological economics. The main concept I study in this paper is agroforestry, whose understanding requires the analysis of both its definitions and its relation to these other key concepts. I applied focused literature review, employing the scientific databases of ScienceDirect and Springer, as well as the Google Scholar search engine. I used relevant academic publications in English, Spanish, and Hungarian. Agroforestry manifests as a sustainable land-use practice, exhibiting myriad ecological, social, and economic advantages both at the level of individual farms and on a broader landscape scale while aligning with agroecological principles. The findings reveal a robust alignment of agroforestry and agroecology with the beliefs and assumptions of ecological economics. All three concepts underline the unsustainability of contemporary farming within a global economy constrained by ecological limits. Agroecology further emphasizes embeddedness in nature, socio-ecological interactions, and recognition of nature's intrinsic value. All three concepts genuinely apply trans-disciplinary approaches, while their shared commitment to systems thinking helps to understand complex human-environment interactions. Synergy between these concepts presents a promising avenue for fostering sustainable food systems amid global environmental challenges.

Keywords: *agroforestry, agroecology, ecological economics, agroecosystems, sustainable food systems*

JEL Codes *O13, Q15, Q56, Q57*

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Introduction

Agroforestry, characterized by the intentional integration of trees or shrubs with crops and/or livestock on the same land, offers a multifaceted strategy to optimize land use while enhancing ecological resilience. Simultaneously, agroecology, as a holistic and interdisciplinary approach, emphasizes the optimization of ecological processes within agricultural systems, fostering biodiversity, soil health, and overall sustainability.

A vast body of literature exists on the individual concepts of agroforestry and agroecology. However, the frequently inconsistent use of these terms creates confusion, and there is a scarcity of analysis regarding their relationship, similarities, and distinctions. I have basically two research questions. What is the relationship between the concepts of agroecology and agroforestry according to the literature? How do the characteristics and the philosophy of agroecology and agroforestry fit into the theoretical framework of ecological economics, given its fundamental assumptions? Finding the answers requires a thorough understanding of the nature of these concepts and their uses.

Hence, this article endeavours to unravel the interconnected nature of agroforestry and agroecology while also delving into their interface with the powerful paradigm of ecological economics, aiming to illuminate pathways towards regenerative and economically viable agricultural systems. The common principles and philosophy they share offer potential solutions for addressing urgent global challenges, including climate change, biodiversity loss, and the imperative for economically resilient food systems.

In this study first I introduce the concept of agroforestry and detail its ecological, economic, and social benefits, as well as some cases of the inadequate applications of agroforestry and misuses of the concept. I also synthesize the conditions found in the literature that allow these benefits prevail. The theoretical framework of agroforestry is provided by the discipline of agroecology. Hence, I provided a definition for the concept of agroecology and highlighted its properties, underscoring the significance of a paradigm shift away from the prevailing production-oriented, industrial agricultural practices. The characteristics of agroecology and agroforestry jointly answer how this approach fits into the paradigm of ecological economics, considering its positions and assumptions.

Materials and methods

I applied focused literature review for this study, on the one hand, to provide a comprehensive description of the three concepts relevant to the topic, on the other, to analyse and describe the relationship between them. I searched for relevant literature in English, Hungarian, and Spanish, combining the search terms "agroforestry", "agroecology", "ecological economics", "environmental economics", "sustainability", "sustainable agriculture", "ecosystem services", and "land use management". I employed the scientific databases of ScienceDirect and Springer, as well as the Google Scholar search engine to have access to information from a broad variety of platforms. My main sources were articles from academic journals and book chapters without a specific time frame, however, I also found relevant international reports, graduate thesis, and books. Specific Springer books and papers on agroforestry were especially useful, due to its wide range of publications in this topic. The relevant items of literature were selected due to their capacity of explaining the concepts studied and in what ways these are interconnected. A thematic classification of the papers was carried out and they were used in the analysis accordingly.

I consider agroforestry as the main concept of the paper. To comprehend it as a multidisciplinary concept and complex socio-ecological system, I focused mostly on its ecological, economic, and social implications, covering these three aspects of sustainability. At the same time, for its broader understanding it was necessary to analyse its conceptual framework and its relation to other key concepts. During my previous readings, I found that there is a strong link between agroforestry, agroecology, and ecological economics as a school of economic thought that has been gaining prominence in recent decades.

The following chapter on "agroecology and agroforestry as agroecological practice" provides a basic overview of the concept of agroecology and describes its relationship with agroforestry. For this chapter it is crucial to understand the different interpretations of agroecology and the historical context in which it emerges as a response to the production-oriented Green Revolution (later explained).

To analyse the nexus of agroforestry and agroecology with ecological economics, I drew upon the insights of prominent scholars in ecological economics, like Røpke and Martínez-Alier. Utilizing their delineation of the fundamental beliefs and foundational assumptions of ecological economics as a reference point, I examined potential overlaps with agroecology and agroforestry. By this stage in the study, building on earlier findings, I presume that agroforestry practices fall within the broader realm of agroecology. Consequently, I integrate them conveniently into the analysis of their alignment with ecological economics.

Agroforestry and its ecological, economic, and social benefits within the literature

One of the most interesting means of resolving the contradictions between agricultural production and forest conservation, combining traditional and innovative methods, is agroforestry, a "form of land use that combines different agricultural sectors by growing woody plants (trees and shrubs) in a given place at the same time" (Keserű et al., 2018:76). Another, broader definition is that "agroforestry is a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels" (Buttoud et al., 2013:38).

Nair et al. (2021) distinguish three major categories of agroforestry systems: agrisilvicultural (crops and trees), silvopastoral (pasture/animals and trees), and agrosilvopastoral systems (crops, pasture/animals, and trees). Due to their structural basis, we can refer to the nature of the components, including spatial arrangement of the woody component, vertical stratification of all the components, and temporal arrangement of the different components. Further, purpose-oriented classification criteria can be the system's function (major role or output), ecological distribution (rainfall, elevation), and its socioeconomic characteristics (subsistence, commercial). Practical examples of this classification systems can be: "an agrisilvicultural system for food production in the lowland humid tropics at a subsistence level of production, a commercial silvopastoral system for fodder and food production in lowland subhumid (or dry) tropics, an agrosilvopastoral system for food production and soil conservation in highland humid tropics, and so on" (Nair et al., 2021:32).

Gyuricza and Borovics (2018) emphasise that agroforestry as a practice worked out well for thousands of years. However, the mechanisation, the use of chemicals, and the emergence of large estate systems, which have accompanied agricultural modernisation in more developed countries, have led to the separation of forestry and crop production, with many negative environmental impacts. Among these, the authors mention environmental problems such as soil erosion, wind erosion, water pollution, carbon release, loss of biodiversity, and reduction of habitats for natural enemies of pests. Climate change will only exacerbate these negative processes. At the same time, the negative social impact of this segregation is that farmers have lost part of their previous sources of income and increased their exposure to market risks by switching to monoculture farming.

The resurgence of agroforestry on a global scale shows that this ancient production method is making a comeback. This renewed interest is driven by its ability to boost productivity and crop quality, ensuring ecological safety. Additionally, it enhances the quality of life in rural areas by providing stable profitability and basic living conditions, offering diverse food options throughout the year (Tewari & Dagar, 2017).

The appropriate use of agroforestry practices can achieve different economic, social, and natural resource conservation objectives simultaneously, making it a beneficial land use in all three aspects of sustainability. In addition to its positive impacts on agricultural productivity and social well-being, experience shows that agroforestry contributes significantly to maintaining biodiversity, increasing connectivity between fragmented landscapes, restoring degraded ecosystems and mitigating and adapting to climate change (Montagnini, 2017). Pantera et al. (2021) highlights the environmental benefits of agroforestry, underlining its potential to create ecologically intensive agricultural production systems. In essence, agroforestry serves as a bridge between agricultural production and ecological considerations, promoting sustainable food security through the judicious use of natural resources. Moreover, it emerges as a promising strategy for developing countries, addressing food and water security, energy needs, and ecosystem and population health (Akamani & Holzmueller, 2017).

Agroforestry systems can provide a wide range of ecosystem services (Raj et al., 2019). Increased crop yields, tree biomass, livestock health and protection, improved soil fertility, efficient water use, increased income through increased production of wood products and Non-Timber Forest Products (NTFPs), promotion and conservation of biodiversity, and carbon sequestration and storage are some of the most important ones (Raj et al., 2022). José (2009) summarises the ecosystem services provided by agroforestry systems and the related international scientific findings in four categories: carbon sequestration, soil improvement, biodiversity conservation, and air and water quality improvement.

On 25 September 2015, UN General Assembly member states adopted 17 Sustainable Development Goals (SDGs), also known as global goals, as part of a new sustainable development agenda to be achieved by 2030. Agroforestry can make a significant contribution to achieving many of these goals, like ending hunger (SDG2) through food security and sustainable agriculture; gender equality (SDG5); affordable and clean energy (SDG7); reducing inequalities within and between countries (SDG10); tackling climate change (SDG13); and protecting terrestrial ecosystems, mainly through sustainable management of forests (SDG15). However, taking into account the interlinkages between the SDGs, agroforestry can also contribute to a much broader set of development goals, such as the first goal of poverty eradication and the third goal of ensuring health and promoting well-being (Montagnini & Metzel, 2017). Noordwijk (2020) argues that agroforestry does not only make a significant contribution to the development goals related to agriculture and forestry separately, but also should be seen as an incentive for policy synergies between the development goals as a whole, due to its interactions with different landscapes.

Agroforestry can also be defined as a complex and adaptive socio-ecological system, based on natural (environmental richness and ecosystem processes as a whole) and human subsystems (the totality of human life skills and social relations, coordination of human activities) complemented by social, productive, and financial subsystems. The sustainability of agroforestry systems can also be assessed through the interaction and interdependencies of these subsystems, with human decisions playing a pivotal role (López et al., 2017). The resilience of an adaptive socio-ecological system, stemming from the interplay between social and ecological systems, can be developed through appropriate ecosystem management. Adapting these systems to change and achieving long-term social, economic, and ecological sustainability requires integrated land and water resource management. This entails considering the geographical scope of ecosystems and incorporating diverse forms of knowledge, including local indigenous knowledge. (Akamani & Holzmueller, 2017).

Given the uncertainties and unpredictability of social ecosystems, adaptive governance is important, which is defined as "flexible and learning-based collaborations and decision-making processes involving both state and nonstate actors, often at multiple levels, with the aim to adaptively negotiate and coordinate management of social-ecological systems and ecosystem services across landscapes and seascapes" (Schultz et al., 2015:7369). For agroforestry systems, this concept is crucial due to issues like government regulations and policies affecting agroforestry globally; alignment of ecosystems with local cultures and farming methods; and synergies between indigenous ecological knowledge and modern science, with practical benefits derived from them, etc.

According to research on trends and conditions for the establishment of agroforestry worldwide (Glover et al., 2013), the most important socio-economic factors that play a role in the adoption of agroforestry by individual farmers are: the possibility of increasing household financial security; access to market information and to markets; secure land tenure for the adoption of a long-term land use system; availability of affordable labour for labour-intensive farming processes; size of landholding, which together with the availability of labour influences the choice of the type of agroforestry system; gender division of tasks within a community; availability of complex knowledge for agroforestry farming, especially the use and combination of indigenous knowledge with scientific knowledge; and appropriate financial incentives and government regulatory environment. At the same time, a number of studies have addressed the involvement of stakeholders, the use of participatory mechanisms in decision-making processes (e. g. collective planning of agroforestry systems) or knowledge transfer processes (e. g. combining indigenous and scientific knowledge, transfer of technological and market information) (Dumont et al., 2019; German et al., 2006; Lacerda et al., 2020).

Lasco et al. (2014) detail the economic and social benefits of agroforestry alongside its ecological functions. The economic benefits include, for example, improved productivity and profitability of farms, diversification of food and income sources, increased income, diversification of income risks and stabilization of livelihoods. Highlighting positive social impacts, the authors note the abundance of food and energy sources accessible to producers during extreme events, the social security derived from the sale of harvested timber during crises, and the diversification of diets through fruit production. After conducting a literature review on climate-smart agroforestry systems, Ntawuruhunga et al. (2023) underscores that the foremost economic and social benefit globally emanating from these land practices is food security. This is attributed to the diversification of species and products, coupled with the higher yields achieved within these systems. Among the positive economic effects, the authors stress that many of the products of agroforestry have a high monetary value and reduce the producer's exposure to external shocks. The high yields of firewood from energy wood plantations, wood for other uses and forest by-products (fruit, fodder, etc.) can produce large quantities of biomass and enable farmers to generate higher incomes than monoculture farming. At the same time, the job creation potential of agroforestry is significant, not only in farming but also within the value chain.

Lehmann et al. (2020) showcasing the productivity and economic advantages of agroforestry systems in Europe, also emphasize the considerable benefit of these systems as a source of organic products. These products can be instrumental in establishing innovative value chains that concurrently contribute to rural development.

A concept often used in studies of the benefits of agroforestry systems is the land parity ratio. This ratio shows "how much land is needed to produce the yield of 1 hectare of agroforestry unit when farming is managed in separate areas of forestry and agriculture" (Honfy, 2023:34). A number of studies based on empirical data from countries with different conditions have used land equivalent ratio (LER) calculations to demonstrate that agroforestry systems implemented on a given unit area can achieve higher productivity than separate monocultures of the same crops (K. Solanki, 2018; Lehmann et al., 2020; Sun et al., 2017; Temani et al., 2021; Utomo et al., 2016; Yang et al., 2021). However, economic returns depend not only on productivity, but also on the quality that enables higher prices. For some crops (e. g. coffee), there is evidence that the ecosystem services provided by agroforestry systems can result in higher quality crops and higher profits than conventional agriculture, despite lower yields (Hernandez-Aguilera et al., 2019).

Some critical studies also address the downsides of agroforestry, when this form of land use does not have the expected positive effects, or the concept is too loosely defined and its use is inherently flawed (Mukhlis et al., 2022; Ollinaho & Kröger, 2021). The absence of agronomic knowledge among farmers to establish synergies between various components in a complex system can prove counterproductive both environmentally and economically. In some instances, expansive plantations funded by private capital give rise to a rigid "industrial" agroforestry model, contributing to species dominance and a decline in biodiversity. "Commercial" mixed plantations, geared towards specific agricultural commodities, can replace intact forests – a form of deforestation that presents significant challenges when attempting to justify it under the label of "agroforestry". It is only in degraded areas outside primary forests that it is recommended to initiate soil improvement and biodiversity restoration using agroforestry methods in a competent manner (Mukhlis et al., 2022).

Ollinaho and Kröger (2021) extend the prior line of reasoning by delineating three distinct types of agroforestry transitions: "the good, the bad, and the ugly". In this classification, the "good" agroforestry transition, or the so-called "agroforestry", stands out as ecologically beneficial for specific regions and contributes to the promotion of social justice. On the contrary, the "bad" agroecology refers to agribusiness forestry, which not only reinforces but institutionalizes large-scale agribusiness practices detrimental to the environment and exacerbates social inequalities. Lastly, it identifies as "ugly" those practices endorsing deforestation or the conversion of natural forests into tree plantations. Labelling these "bad" and "ugly" practices as agroforestry aims to present them as sustainable, although they unmistakably fail to align with the acknowledged definitions of agroforestry, inclusive of the sustainability criteria mentioned earlier.

García de Jalón et al. (2018) studied key stakeholders' perceptions on the implementation and expansion of agroforestry in 11 countries of Europe, including its positive and negative aspects. The positive aspects of agroforestry identified by stakeholders were primarily environmental or production benefits, specifically, enhanced biodiversity and wildlife habitats, landscape aesthetics, soil conservation, and animal health and welfare. Meanwhile, main negative aspects were linked to management and socio-economic factors, including increased labour, complexity of work, management costs, the administrative burden and occasional predation by wild animals. According to the evidence of environmental and societal benefits perceived, authors propose four ways to promote agroforestry: national demonstration sites and education programs; improved regulation; providing a market for the positive externalities with agroforestry; and increasing the opportunities for new profitable businesses. The emphasis on these issues shows that the main constraints of wider adoption in Europe are mainly related to the political and economic environment.

Torralba et al. (2016) draw similar conclusions. Their meta-analysis based on 53 publications reveals that agroforestry typically boosts biodiversity and the provision of ecosystem services compared to traditional agricultural and forestry practices in Europe. Nevertheless, the considerable variability in outcomes underscores the influence of biophysical factors and land-use conditions. Its success largely depends on the consideration of its inherent complexity in policy measures.

Further articles recognize overall positive environmental effects of agroforestry and address the importance of adequate economic and policy environments, flexible enough to adapt to local ecological and cultural circumstances, added to effective cooperation and knowledge transfer between key stakeholders (Pantera et al., 2021; Santiago-Freijanes et al., 2018). There are few studies at national or regional level on the complex environmental, social, and economic impacts of agroforestry, and as a result, policy makers lack confidence in this form of land use. This hampers the wider uptake of agroforestry (Mukhlis et al., 2022; Ollinaho & Kröger, 2021). The systematic literature review processing 591 primary articles and 41 other systematic literature reviews from 31 countries, conducted by Castle et al. (2022), evidences that topics like regulating ecosystem services outcomes and agricultural productivity of agroforestry in different contexts are well studied, while evidence on human well-being remains limited. The study highlights that there is limited information available regarding the effects of specific policy measures aimed at encouraging agroforestry. This gap in scientific research on agroforestry matches with the shortcomings in properly elaborated economic and policy incentives in a wide range of countries.

1. Table: Possible advantages of agroforestry and their conditioning factors

Possible advantages		Conditions to avoid negative outcomes
Ecological	Improved soil fertility; efficient water use; increased connectivity between fragmented landscapes; promotion and conservation of biodiversity and wildlife habitats; carbon sequestration and storage (mitigation and adaption to climate change). (Gyuricza & Borovics, 2018; Jose, 2009; Montagnini, 2017; Pantera et al., 2021; Raj et al., 2019b, 2022)	Biophysical practices that enhance the overall biodiversity and soil ecosystems of the local environment and gradually increase the average age of perennial cultivation. Planting native tree species, other perennials and food crops using agroecological principles. Appropriate ecosystem management, integration of indigenous knowledge. (Akamani & Holzmueller, 2017; Lacerda et al., 2020; López et al., 2017; Mukhlis et al., 2022; Ollinaho & Kröger, 2021)
Social and economic	Diversification of income risks and stabilization of livelihoods; abundance of food (food security) and energy sources (available biomass); water security, evidence of higher productivity (LER); diversification of diets; reduction of social inequalities; overall health of the population. (Akamani & Holzmueller, 2017; Dagar & Tewari, 2017; Hernandez-Aguilera et al., 2019; Honfy, 2023; Lasco et al., 2014; Lehmann et al., 2020; Montagnini, 2017; Montagnini & Metzel, 2017; Noordwijk, 2020; Ntawuruhunga et al., 2023)	Access to market information and to markets; secure land tenure for the adoption of a long-term land use system; availability of affordable labour for labour-intensive farming processes & size of landholding influences the type of agroforestry system; gender division of tasks within a community; availability of complex knowledge for agroforestry farming (indigenous knowledge & scientific knowledge); effective involvement of stakeholders in decision-making processes; training opportunities; and appropriate financial incentives and government regulatory environment. (Akamani & Holzmueller, 2017; Dumont et al., 2019; García de Jalón et al., 2018; German et al., 2006; Glover et al., 2013; Lacerda et al., 2020; López et al., 2017; Schultz et al., 2015)

Own elaboration based on the corresponding authors.

Agroecology and agroforestry as agroecological practice

The scientific framework of agroforestry from the perspective of sustainable food production is provided by agroecology, a very broadly applied, multi-disciplinary philosophy. This broad applicability also makes the term somewhat difficult to be defined. Rivera-Ferre (2018) argues that there are competing interpretations of the concept worldwide, and highlights three main interrelated approaches and interpretations of agroecology: agroecology as an agricultural practice, agroecology as a social movement, and finally agroecology as a discipline. Várallyay (2005) who adopts the latter approach, defines agroecology as "the field of ecological research that studies the causal relationships between populations in agricultural areas, human-regulated ecosystems and their environment" (p. 1).

A FAO (2018) The definition of agroecology obviously favours the agricultural approach, but it also reflects the broad, multidisciplinary nature of agroecology: "Agroecology is an integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agricultural systems. It seeks to optimize the interactions between plants, animals, humans, and the environment while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system" (p. 1).

Emphasising the social aspects Altieri and Nicholls (2012) formulate the essence of agroecology as a transition from industrial agricultural systems based on fossil fuels and exports to an alternative agricultural paradigm. The latter would primarily be based on local and national food supply by dynamizing smallholder, family farms, building on peasant innovation, local resources, and solar energy. This will require access to land, seeds, water, credit, and local markets, as well as substantial public support, which is in fact a short summary of the land reform programmes of some developing countries.

Ujj & Fehér (2016) stress the importance of combining traditional peasant knowledge with modern agroecological knowledge. In this way, it is possible to optimise farming systems by applying a holistic approach to farming. Koohafkan & Altieri (2011) argue that agroecological systems are based on the ecological rationality of traditional agriculture, which has created thousands of successful agricultural structures. They have a wide variety of crops and domesticated animals, while being sustained by ingenious soil and water management and biodiversity systems derived from indigenous knowledge.

Rivera-Ferre (2018) in distinguishing between the three main conceptual understandings, adds that there are also different narratives within each approach, which can lead to different policy proposals. Generally speaking, a common thread across the field is the opposition to ecologically unsustainable industrial agriculture. Gómez-Echeverri et al. (2020) underline that agroecology has emerged as a response to the negative environmental and social impacts[2] of the so-called Green Revolution[3], which increased productivity and was based on the principles of neoclassical economics. To briefly synthesise its meaning, agroecology aims to transform food systems to achieve sustainability, according to the principles of ecological responsibility, economic viability and social equity (Gliessman et al., 2007).

Agroecology therefore represents a paradigm shift from production-oriented, industrial agriculture. The differences between the two approaches are summarized by Sarandón & Flores (2014) in the following table:

[2] Increasing dependence on agrochemicals; contamination of food, water and soil and damage to health; development of resistance of certain pests and pathogens to pesticides; loss of soil productivity, nutrient loss; eutrophication of water resources, reduction of aquifer water supply; increasing dependence on fossil fuels and decreasing energy efficiency; loss of biodiversity; loss of genetic variability of major crops; displacement of some traditional farming techniques by supposedly universal 'modern' technologies (cultural decline); it contributed to global warming and ozone depletion; was not applicable to all farmers and did not solve the problem of rural poverty (Sarandón & Flores, 2014).

[3] The Green Revolution represents a significant increase in agricultural productivity and the widespread adoption of industrial agriculture, achieved from the mid-20th century onwards using modern technologies such as improved crop varieties, fertilisers, and irrigation.

2. Table: Differences between production-oriented and agroecological approaches

Production-oriented approach, intensive agricultural production	**Agroecological approach, sustainable agriculture**
Reductionist	Holistic (aiming for completeness)
There is only one kind of agriculture	There are several ways of farming
Ethics is a "vague" value	Ethics is a core value
Lack of a systemic approach	Using a systemic approach
The importance of the components	The importance of interactions
Reducing or wrong definition of system boundaries	Broadening and redefining system boundaries
Recognises only scientific knowledge	It recognises scientific and also other types of knowledge
"Local" is not important	The "local" is important, endogenous potential
One use of the site	Multiple uses of the area: food, tourism, landscape, ecological services
Reduces the importance of socio-cultural aspects	The importance of socio-cultural aspects
Mainly based on input technologies	Mainly based on process technologies, minimising inputs
Technology created exclusively by scientists	The farmer is involved in the creation of the technology
Goals	
Short term	Long term
Production-oriented	Sustainability-focused
Focus on productivity	Focus on agroecosystems and related ecosystems
The economic analyses do not include environmental costs. "The false illusion of wealth"	Economic analyses include environmental costs.
Simple systems, low biodiversity (instability)	Complex systems, high biodiversity (stability)
Biodiversity is seen as a genetic resource	Well-functioning biodiversity is an essential structural, life-sustaining factor in agroecosystems

Agroecology studies the functioning of agroecosystems as practical, functional systems and promotes their practical sustainability. An agroecosystem is "any combination of habitats and organisms that are consciously influenced and regulated by humans in different ways, at different times, and at different grades." (Várallyay, 2005:1). The key challenge in designing sustainable agroecosystems is to simultaneously maintain natural ecosystem characteristics and sustain productivity. To achieve this, first, the energy flow must be designed in a way that relies less on non-renewable inputs provided by humans and creates a balance between the energy flowing inside and out of the agroecosystem, mainly in the form of harvest. The second characteristic of a sustainable agroecosystem is that population control mechanisms operate within a system that, by increasing the number of habitats and allowing natural enemies to be present, enhances overall resistance to diverse pests and diseases. Finally, the third characteristic is the incorporation of attributes such as productivity, stability, viability, resilience, adaptability, equity and self-sufficiency, in order to provide the agroecosystem with the conditions to achieve a dynamic balance and thus a sustainable system (Gliessman et al., 1998). The structure of an agroecosystem is "the configuration or internal spatial arrangement of the broader agroecosystem, along with the interplay between its diverse sectors and vegetation corridors or production systems, facilitates the movement and interchange of various animal and plant species. This structure offers shelter, habitat, and sustenance, contributing to microclimatic regulation and influencing aspects such as production, the conservation of natural resources, and other ecosystems, as well as cultural considerations" (León Sicard, 2014).

Agroforestry in agroecological literature is mostly understood as sustainable land use and agricultural practices that adhere to agroecological principles (Rivera-Ferre, 2018; Rosati et al., 2021). "Agroforestry is an agroecological approach based on the diversification of the agroecosystem production components (trees/shrubs, crops and/or livestock) and on the intensification of the agroecological relationships that exist between these components in space and time" (Rosati et al., 2021).

Wezel et al. (2014) argue that different types of agroforestry practices can be considered agroecological practices, as they reduce nutrient leaching, conserve soil, increase the diversity of the production system, and produce wood for various uses. Prabhu et al. (2015) conclude that there is growing evidence in the developing world that the use of agroforestry as an agroecological approach helps to restore the productivity and resilience of landscapes and contributes to food and income security for smallholders and other vulnerable groups in society. At the same time, the study concludes that although many of the ecological, social, and economic benefits of agroforestry have been demonstrated at farm and landscape scales, further investment and policy support is needed worldwide to take agroecology's practical potential to the next level and to truly unleash its potential on a large scale.

A nexus explored: the bond between Ecological Economics, Agroecology, and Agroforestry

Ecological economics' understanding of the relationship between the economy and nature differs from neoclassical environmental economics: it sees the economy as a subsystem of nature, since "no human economy can be imagined without the general life-support and other specific services of nature." (Pataki & Takács-Sánta, 2005). In his classic paper Boulding (1966) illustrates the divergence between two paradigms using the metaphors of the "cowboy economy" and the "Earth-spaceship economy". In the "cowboy economy", the expanses available for occupation and exploitation are deemed infinite. Consequently, both consumption and production, driven by the material transformation of production factors in the presence of seemingly boundless resources, are perceived as limitless and inherently desirable goals. In contrast, within the framework of a "spaceship economy" operating in a closed system, the resources available for exploitation and the potential for pollution are not infinite but restricted by the finite capacity of Earth's ecosystems. A crucial distinction lies in the fact that, contrary to the tenets of neoclassical economics, this economic concept seeks to minimize the material conversion capacity.

There is also a debate between environmental economics and ecological economics approaches on the concept of sustainability. The difference between so-called weak and strong sustainability can be described through the relationship between natural capital and economic capital. According to Szlávik's definition (2005:27-28) weak sustainability means the unlimited substitutability of nature: "According to this view, depleted natural capital can be freely replaced by economic capital. It follows, inter alia, that the combined value of the capital stock (natural and artificial capital) cannot be reduced (...) Therefore, in the extreme case, a world without nature is a reality, where the functions of nature are taken over by the economy." On the contrary, the concept of "strong sustainability" emerged within ecological economics, asserting that "natural capital must be preserved, as natural and human-made capital can only be substituted for each other to a limited extent."

Substantial differences exist between the two approaches regarding the substitutability of natural capital for economic capital. These differences extend to matters such as the influence of economic growth and international trade on the natural environment, the role of technological change and innovation in sustainability, the correlation between economic growth and quality of life, and the perspective on the valuation of nature. "Ecological economists are more sceptical towards the possibilities for substitution, more critical towards the positive impacts of growth and trade, have less trust in the positive potential of technological change, are sceptical towards the idea that quality of life improves with economic growth in the rich countries, and more readily accept that nature has intrinsic value" (Røpke, 2005:275).

Given its distinctive features, it can be asserted that agroecology aligns with the theoretical framework of ecological economics in terms of the relations between economy and ecology. However, comprehending this connection requires a brief overview of the relevant aspects of the approach of ecological economics.

The founders of ecological economics share the concept of the economy as embedded in nature; the importance of nature as a life-support system; and the centrality of analysing ecological and economic systems and their interactions in terms of energy and material flows. Røpke (2005) briefly summarises the basic beliefs and founding assumptions of ecological economics:

- Because nature sets the limits of the economy, ecological economics argues that our economy has already reached or exceeded its maximum sustainable scale.
- The economy is embedded in a broader social and cultural system with nature, economy, society, and culture evolving together. Therefore, social, and institutional aspects must be included in the analysis of the economy.
- A trans-disciplinary approach and cooperation between disciplines is essential to understand environmental problems and develop solutions.

- The starting point of ecological economics is basic ignorance, that we do not know enough about nature and the interactions between humans and their environment. We must deal not only with general uncertainty, but also with not knowing what we do not know: that is, human intervention in nature can have a range of unintended consequences.
- The former involves applying systems thinking to dynamic processes, combining the traditions of natural sciences and economics.
- Considering the interests of future generations, the scale of economy needs to be limited, so equity and income distribution come to the fore. The latter is necessary to ensure that poverty eradication is not pursued through further, environmentally destructive growth.
- Nature has intrinsic value and is important not only because of people's needs.

One of the key concepts in ecological economics is social metabolism, which refers to the energy and material flows in the economy. "It measures the links between economic growth and use of energy and tests the absolute or relative dematerialization of the economy (relative to GDP) by studying material flows" (Martínez-Alier, 2012:52). In its general formulation, metabolism between nature and society begins when a group of people takes up materials and energy from nature (input) and ends when they dispose of their waste, emissions and residues in natural spaces (González de Molina & Toledo, 2014). Although modern farming has increased productivity per unit of work and per hectare, it has substantially reduced energy efficiency (Leach, 1975; Martínez-Alier, 2012). Some authors stress that achieving necessary yield growth faces constraints under the current paradigm due to resource and environmental factors in various regions. Balancing yield requirements with ecological constraints is crucial, highlighting the need for regional sustainable agroecosystem models. Additionally, demand-side factors like population policy, consumption efficiency, and equitable distribution become crucial in a world of constrained agricultural growth (Altieri & Nicholls, 2012b; Harris, 1996).

There is an intense global debate of the possibilities and limits of scaling up alternative agricultural practices based on agroecological principles in order to feed a growing world population (Dalgaard et al., 2003; Gomiero, 2018; Pittelkow et al., 2015; van der Ploeg et al., 2019). The ongoing discussion includes issues like the effects of alternative agricultural practices on yields, their scalability, their feasibility under different farming contexts, and its maturity as a scientific discipline. Gomiero (2018) for example underlines that non-growth advocates want a more frugal lifestyle for agriculture based on local production and food self-sufficiency, low-input farming, and short food chains. However, according to the author, there is little evidence available to show how such systems can ensure the food security of an entire country, what the impact on social metabolism would be, or what direction society would have to take to become fully reliant on such alternative farming practices.

The importance of a trans-disciplinary approach and the need for a broader cultural and social system as a framework for analysis, which are basic assumptions of ecological economics, are also part of the foundational principles of agroecology and agroforestry. Many studies emphasise the importance of this approach to agroforestry systems research and landscape management strategy planning, especially the involvement of social sciences. This is particularly necessary for a holistic understanding of socio-ecological interactions in agroforestry systems, as solving institutional, cultural and social management problems in landscape management requires combining our biophysical knowledge with other forms of knowledge (Parker & Burch, 1992). On the other hand, it is essential to involve a wide range of key actors, to understand the economic costs of the transition, and to research and communicate the longer-term benefits of agroforestry in order to achieve wider adoption (Udawatta & Godsey, 2010).

A trans-disciplinary approach is needed to take account of the economic and social realities of agroforestry. The reasons for the social acceptance and use of this form of farming can be complex. In addition to economics and the operational efficiency of the system, aspects such as the values held by a given community, local land tenure relations, or the marketability of agroforestry products may also play a role (Montambault & Alavalapati, 2005). In an era of accelerated climate change, helping farmers to adapt to environmental change in a dynamic way based on indigenous knowledge also depends on our ability to understand, through research, the heterogeneous local ecological, social, cultural, and economic contexts and conditions for adopting agroforestry practices. Development policies and incentives must be adapted to these conditions (Lasco et al., 2014).

Contrary to the quantitative monetary valuation approach in environmental economics, which assumes comprehensive knowledge of nature's goods and services, ecological economics posits that our understanding of ecology is incomplete. The thesis underscores the limited knowledge about nature and the consequences of human activities on it. Ecosystems, intricate and regulated systems resulting from the interdependent associations of living organisms with the inanimate environment, are profoundly complex, where any single effect reverberates throughout the entire system. (Vida, 2001). Málovics (2020:39) explains in this context that "there is a high degree of uncertainty surrounding the nature of global biodiversity and its destruction, and the most effective means of halting this destruction. This situation is underpinned by the fact that if a species is removed from the ecosystem, the consequences cannot be known in advance because its role in the ecosystem and its impact on ecosystem functioning cannot be known." Norgaard (1985) in his critique of environmental economics, draws attention to the complex dynamic interdependencies of environmental systems, which contradict economic models based on classical mechanical concepts that break down the system into its components.

Undisturbed natural systems, like part of the Amazon Basin, which provide habitats for an unprecedented number of species, are useful to illustrate this problem. As the number of connections within the ecosystem increases exponentially with the number of components, our taxonomic knowledge does not provide enough support for ecology to map these linkages (Norgaard, 1981). In such a complex system, uncertainty increases, and the consequences of any human intervention are extremely difficult to predict. In this case, a large amount of information is needed to properly manage socio-ecological interactions, e.g. in agricultural production systems adapted to local conditions. Therefore, production technologies developed in temperate, less diverse ecosystems cannot be effectively applied in the Amazonian context, while the economic exploitation of high-value species is hampered by the physical presence of commercially "low-value species" that play a vital role in the system as a whole (Norgaard, 1981).

The study of agroecology, understanding the interactions between nature and society and between global, national, and local processes, imply the need for systems thinking. The intricate interplay of environmental, economic, and social dynamics, coupled with market forces, agricultural policies, cultural nuances, and historical context in a specific region, go far beyond the scope of agronomic analysis. Addressing the complex, challenging processes of anthropogenic climate change necessitates a holistic systems approach. (Casanova et al., 2016). Examining the agroecosystem as an intricate network of interconnected elements aligns seamlessly with the systems and multidisciplinary approach characteristic of ecological economics.

The concept of natural capital, which includes renewable and non-renewable resources, is connected to the so-called concept of ecosystem services. This concept emphasises the importance of ecosystems as factors without which any human economy, prosperity and social development would be impossible (de Groot & Braat, 2015). Ecosystem services are generated by ecosystem processes, which are the result of biodiversity (Málovics, 2009). Like ecological economics, which takes an ecosystem approach to understanding the links between the economy and the environment, agroecology emphasizes the application of ecological principles to agriculture, viewing farms as ecosystems (see the previously mentioned concept of agroecosystem).

A key principle in agroecology emphasizes minimizing external inputs and efficiently utilizing endogenous potential. One key focus within ecological economics research is the effective and sustainable utilization of natural resources, incorporating traditional ecological knowledge. The acknowledgment and practical implementation of this knowledge in agriculture have seen increased prominence since the indigenous rights movements of the 1980s (Reyes-García, 2015). The agroecological approach has a fundamental interest in non-scientific, traditional forms of knowledge, while a significant body of research on agroforestry deals with indigenous technologies from all over the world (McNeely & Schroth, 2006; Montambault & Alavalapati, 2005).

Conclusions

Agroforestry is a sustainable land use practice with multiple ecological, social, and economic benefits at the farm and landscape scales that adheres to agroecological principles. Agroecology can be defined as a practice, as a social movement, or a discipline. It embodies an alternative approach with ecological principles to the design and management of food and agricultural systems, and is opposed to ecologically unsustainable, large-scale industrial agriculture.

Agroforestry and agroecology align with the principles and assumptions of ecological economics. They share the idea that our modern farming and food systems are part of an unsustainable global economy constrained by ecological limitations. Agroecology aligns with the principles of embeddedness in nature, an emphasis on socio-ecological interactions, and the recognition of the intrinsic value of nature. The trans-disciplinary approach, a cornerstone of ecological economics, is inherent in both agroecology and agroforestry. These concepts embrace systems thinking, necessary to understand ecosystems and complex human-environment interactions. Within their own fields, agroecology and agroforestry address equity and distribution issues, key to limit ecologically destructive growth.

While evidence supports agroforestry's potential, further global investment and policy support are essential to realize its practical potential on a larger scale.

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