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Abstract	Duru et al. (Agron Sustain Dev 35:1259-1281, 2015) highlighted a missing tool for studying and improving the performance of cropping systems in the transition to highly diversified agriculture. In response, this paper proposes a concept for designing, modeling, monitoring, and auditing desired ecosystem services, in intercropping and agroforestry systems. This concept delimits the smallest spatial unit called ESSU, encompassing all the interacting species and other functional components (e.g., crops, trees, livestock, spontaneous vegetation, semi-natural habitats such as hedges, ditches, and forest patches, and eventually animals) that together provide a specified set of ecosystem services. The novel ESSU concept allows representation of an entire diversified agroecosystem by the repetition of the spatial unit that provides the same sets of targeted ecosystem services as the agroecosystem it represents. It can then be used for various activities, such as the (i) design of more efficient agroecological systems according to the targeted ecosystem services; (ii) rapid audit of farming practices for biodiversity/resilience across large tracts of farmland as part of achieving Sustainable Development Goal 2 targets of sustainable food production systems; and (iii) modeling such diversified agroecosystems using a motif adapted to represent the targeted ecosystem services and the species spacing design. We demonstrate that the ESSU concept is highly flexible and applicable to a wide range of diversified agroecosystems, with applications for arable intercropping, crop-tree intercropping, tree-tree agroforestry systems, and agro-sylvo-pastoralism. We also show its relevance and suitability for representing temporal changes over 1 year, across several years, and over decades, indicating its generalizability and flexibility. We argue that ESSU could open new theoretical and practical research avenues for the study of diversified agroecosystems. Considered with all the knowledge available on practices, biodiversity, and ecosystem services, ESSU might provide a learning-support tool to fill the knowledge gap about relationships among practices, biodiversity, and associated ecosystem services.

Keywords (separated by '-')	Agroecolgy - Ecosystem services - Intercropping - Agroforestry - SDG 2
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REVIEW ARTICLE

The ESSU concept for designing, modeling, and auditing ecosystem service provision in intercropping and agroforestry systems. A review

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Abstract

Duru et al. (Agron Sustain Dev 35:1259-1281, 2015) highlighted a missing tool for studying and improving the performance of cropping systems in the transition to highly diversified agriculture. In response, this paper proposes a concept for designing, modeling, monitoring, and auditing desired ecosystem services, in intercropping and agroforestry systems. This concept delimits the smallest spatial unit called ESSU, encompassing all the interacting species and other functional components (e.g., crops, trees, livestock, spontaneous vegetation, semi-natural habitats such as hedges, ditches, and forest patches, and eventually animals) that together provide a specified set of ecosystem services. The novel ESSU concept allows representation of an entire diversified agroecosystem by the repetition of the spatial unit that provides the same sets of targeted ecosystem services as the agroecosystem it represents. It can then be used for various activities, such as the (i) design of more efficient agroecological systems according to the targeted ecosystem services; (ii) rapid audit of farming practices for biodiversity/resilience across large tracts of farmland as part of achieving Sustainable Development Goal 2 targets of sustainable food production systems; and (iii) modeling such diversified agroecosystems using a motif adapted to represent the targeted ecosystem services and the species spacing design. We demonstrate that the ESSU concept is highly flexible and applicable to a wide range of diversified agroecosystems, with applications for arable intercropping, crop-tree intercropping, tree-tree agroforestry systems, and agro-sylvo-pastoralism. We also show its relevance and suitability for representing temporal changes over 1 year, across several years, and over decades, indicating its generalizability and flexibility. We argue that ESSU could open new theoretical and practical research avenues for the study of diversified agroecosystems. Considered with all the knowledge available on practices, biodiversity, and ecosystem services, ESSU might provide a learning-support tool to fill the knowledge gap about relationships among practices, biodiversity, and associated ecosystem services.

Keywords Agroecolgy · Ecosystem services · Intercropping · Agroforestry · SDG 2

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Contents

1 Introduction

This review deals with the discipline of agroecology that seeks to enhance ecological processes to support the production of agricultural goods and ecosystem services (e.g., Wezel et al. 2009; 2014). Agroecology is increasingly being accepted as a discipline to simultaneously: (i) produce food, forage, bio-energy, and bio-components; (ii) protect the environment (soil, air, water), ecosystem diversity, and the planet against climate change; and (iii) safeguard human health, particularly by reducing pesticide use (e.g., Vandermeer 1995; Deguine et al. 2017; FAO 2018). Agroecology may also favor both the adaptation to and mitigation of climate change by enhancing the resilience of agroecosystems (Wezel and David 2012; Saj et al. 2017) and sequestering carbon in soils and trees (e.g., Altieri and Nicholls 2017). Duru et al. (2015) framed agroecology as a "diversity-based agriculture" where a high level of biological diversity replaces chemicals and other external inputs by providing ecosystem services.

Diversified agroecosystems can be conceived in two dimensions: (i) in time, with crop succession of various species in cropping systems based on arable and forage crops; and (ii) in space, where species are grown together in the same space, such as through intercropping and agroforestry systems. Considering the spatial dimension, intercropping is commonly used for describing an association of at least two species (annual or perennial plant species, and/or possibly livestock species) grown or raised together in the same space and where at least one species provides a production service. Intercropping systems, in a broad sense, as used by Willey (1979a, b) and Vandermeer (1992), are based on multispecies plant mixtures. They include a wide range of agroecosystems like arable crop mixtures (Gaba et al. 2015; Hu et al. 2016), multi-service cover crops (Justes and Richard 2017; Garcia et al. 2018), permanent sown grasslands (Violle et al. 2015), woody polycultures (e.g., Lovell et al. 2017), and the wide diversity of agroforestry systems (e.g., van Noordwijk et al. 2019) (Fig. 1).

Considering the temporal dimension, diversification can also be implemented "through time in the same unit of space" like in arable cropping systems (e.g., crop rotation) and in tree-based agroecosystems (e.g., agroforestry trajectories; Jagoret et al. 2018). Both spatial and temporal dimensions of crop diversification are often intertwined, as evidenced by the evolution of different vegetation strata in complex systems such as cocoa-based agroforestry systems (Jagoret et al. 2011; 2017; Deheuvels et al. 2012). Species diversification in space and time is used to provide and enhance ecological processes that support multiple ecosystem services (Garcia et al. 2018; Nijmeijer et al. 2019). Likewise, field management techniques and spatio-temporal patterns of plant species assemblages can be used as levers to reduce the dependence on chemical inputs and fossil energy by providing ecosystem services (Gurr et al. 2003; Swift et al. 2004; Médiène et al. 2011). These examples underline that biotic and abiotic interactions within the agroecosystem can be managed in ways that confer robustness, resilience, and sustainability to agroecosystems while reducing the use of external inputs and their associated negative externalities.

We hypothesize that diversified agroecosystems can be analyzed and represented by the ecosystem services cascade framework (Fig. 2). In this framework, ecosystem services are defined as contributions that ecosystems make to human well-being (Haines-Young and Potschin 2010; 2016; 2018) and result from a cascade of ecological processes and ecosystem functions. Ecological "processes" define how living organisms perform specific activities in the ecosystem and interact with their biotic and abiotic environments. In contrast, "functions", usually resulting from a combination of processes indicate the capacities or capabilities of the agroecosystem to realize something potentially useful to people and also to agroecosystem functioning itself (Haines-Young and Potschin 2010; 2016; 2018). Both processes and functions depend on the spatial structure of the ecosystem and may be strongly determined by species composition, diversity (Balvanera et al. 2006; Diaz et al. 2007; Lavorel et al. 2013), and management (Quétier et al. 2007; Médiène AQ2 et al. 2011; Duru et al. 2013). Ecosystem services give rise

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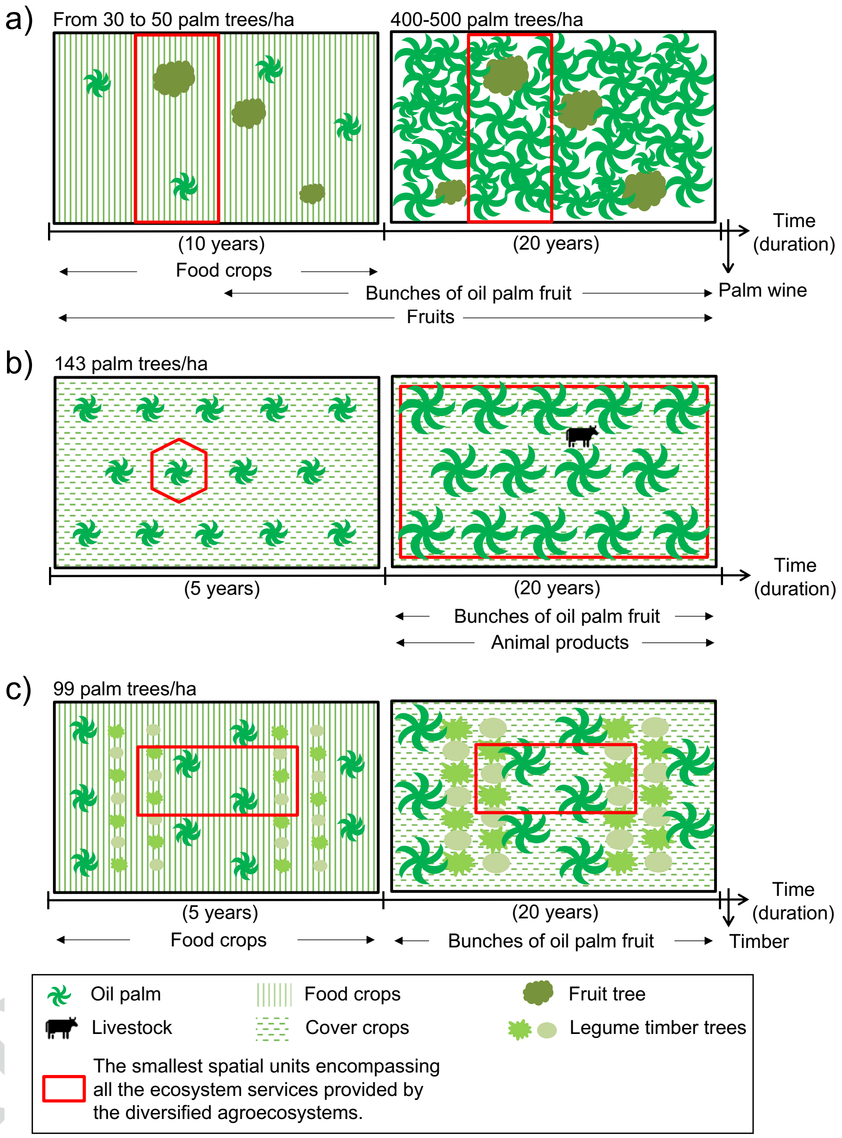

Fig. 1 The smallest spatial unit encompassing all the provided ecosystem services used to describe, represent, and compare different designs of oil palm agroforestry systems and the ecosystem services they provide over the years (Masure et al. 2023).

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to goods that benefit humanity, usually in social, cultural, and technological realms (e.g., food transformation and consumption). Managing ecosystem services requires identifying beneficiaries' specific needs and expectations. Also, judging whether an ecosystem function can be considered a service is strongly context-dependent and must account for biophysical and socioeconomic dimensions (Haines-Young and Potschin 2018).

Following the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2013), ecosystem services are grouped into three categories:

- provisioning services, that is, *nutritional, non-nutritional materials, energetic, and abiotic outputs from ecosystems*;
- regulation and maintenance services, that is, *mediation or moderation of the ambient environment by living organisms or non-living processes that affect human well-being*; and
- cultural services, that is, *non-material biotic or abiotic outputs of ecosystems that affect physical and mental states of people*.

We define a targeted ecosystem service (TES) as an ecosystem service that farmers and stakeholders value. It shapes their choices regarding diversity when managing, designing, or optimizing a diversified agroecosystem. Depending on the complexity of the agroecosystem, the number of TESs can vary considerably and may change through time, following the production cycles and the composition of the plant communities, especially for perennial crops and trees. Gaba et al. (2015) consider that the main challenge for the transition towards a more sustainable agriculture is to design new cropping systems where the plant diversity and associated

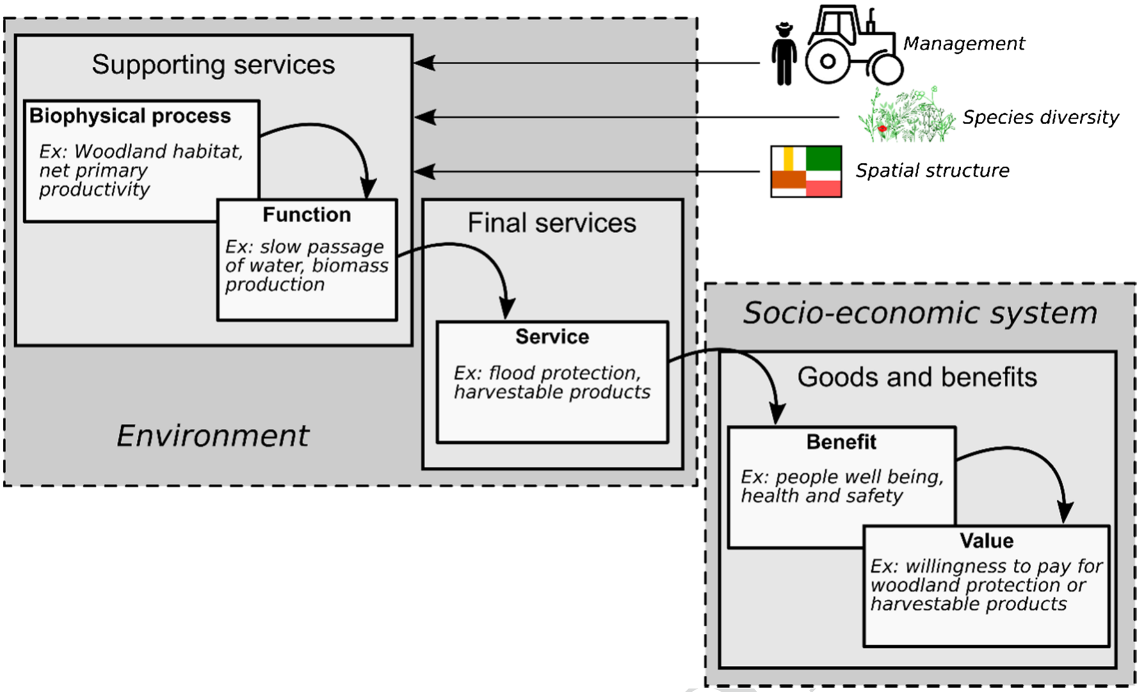

Fig. 2 The present work builds on the ecosystem service cascade framework where ecosystem services are defined as "contributions that ecosystems [including agroecosystems or managed ecosystems] make to human well-being" (adapted from Haines-Young and Potschin 2010; 2016; 2018).

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management practices can deliver a set of TES in given conditions.

Ecological functions have a pivotal role between ecosystems and human activities as they reflect the aggregated, visible, and manageable subset of subtending ecological processes (de Groot et al. 2002; Haines-Young and Potschin 2016). Ecological functions can be evaluated using biophysical proxies to study the ecological (e.g., effects of diversity) and agronomic (e.g., effects of management) determinants of ecosystem services in varying contexts (Lavorel et al. 2013). In agroecosystems, the ecological functions and services usually rely on a limited number of spontaneous or managed species (e.g., sown or planted vegetation or introduced animals) and may be enhanced by management (e.g., conservation, or biological control). Each function relies on a specific combination of (i) plant and/or animal diversity; (ii) functional properties of this diversity; (iii) its arrangement in space and time; and (iv) farmers' management strategies. Some services are provided continuously along one crop cycle (e.g., soil organic matter improvement), while other services are provided at points in time or over given time scales according to abiotic and biotic conditions. Consequently, it is essential that agroecosystem management takes into account the dynamics of the provision of ecosystems services (Schipanski et al. 2014; Garcia et al. 2018).

However, Duru's et al. (2015) review article suggests "a doubly challenging research agenda for the development of (i) knowledge about relations among practices, biodiversity and associated ecosystem services and (ii) learning-support tools used in an adaptive management perspective." Searching for a possible solution to the challenges identified by Duru et al., we imagine that a new concept dealing with agroecology and linking agroecological principles and practical applications, could:

1. generate new knowledge by incorporating biodiversity considerations in agroecosystems through (i) species spacing design; (ii) identifying the TESs provided by these species; and (3) accommodating the effects of management practices like the use of farm machinery
2. be used as a learning-support tool for assessing complex and adaptive agroecosystem dynamics.

Based on very recent and ongoing investigations, this paper proposes a unified definition of a concept developed in recent investigations (Raffiegeau et al. 2019; Masure et al. 2022, 2023) for designing, modeling, and auditing desired ecosystem services in diversified agroecosystems. As a definition, the concept delimits the smallest spatial unit encompassing all the interacting species and other functional components (e.g., crops, trees, livestock, spontaneous vegetation, semi-natural habitats such as hedges, ditches, and forest patches) that together provide a specified set of ecosystem services represented in a farming landscape. We have labeled this smallest spatial unit the “Ecosystem Services functional Spatial Unit” (ESSU) to highlight its spatially recurring combination of characteristics within a farming landscape. Its repetition in space allows representation of an entire diversified agroecosystem. The main value of the ESSU concept lies in its capacity to represent simply the targeted ecosystem services of diversified agroecosystems.

The ESSU concept can be utilized by researchers, farmers, and agricultural advisers dealing with the biological complexity of diversified agroecosystems and seeking to design, model, and audit farming systems to maximize desired ecosystem services. Because of its capacity for use across a broad range of cropping systems and scales (plot, farm, and territory) within farming landscapes, it has potential applications in monitoring and evaluation in the efforts to address Sustainable Goal 2: Zero Hunger, particularly Target 2.4 (United Nations Sustainable development Goals 2022):

> By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.

We first propose such a concept because there is no agronomical concept corresponding to the computer science concept of a simplified scene of the system when modeling a diversified agroecosystem. Secondly, agronomists do not use a concept to represent a whole system integrating cultivated species, spacing design, technical management, the TES, and their provision areas, which are necessary for designing diversified agroecosystems. Thirdly, we need to represent and compare agroecosystems when auditing the TES they provide, and ESSU could be the simplified representation of the system.

Technical support is still mainly based on agrochemicals and the labor force rather than on services provided by introducing biodiversity in agroecosystems. In addition, advances in agricultural and ecological sciences are necessary to better predict the effects on biodiversity in agroecosystems in response to planned modifications of agroecological practices from field to landscape level (Duru et al. 2015). The importance of developing such knowledge, tools, and capacity is heightened with the urgency of the UN’s 2030 SDG Target 2.4 to “ensure sustainable food production systems and implement resilient agricultural practices.”

The “Ecosystem Services functional Spatial Unit” (ESSU) proposed here is designed to accommodate the biological and structural complexity of diversified agroecosystems. The ESSU concept aims to broaden the conceptual tools of agronomy to facilitate uptake of agroecological approaches for dealing with a continuum of diversification in agroecosystems and ecosystem services. Our concept could fill the knowledge gap identified by Duru et al. (2015). The originality and strength of the ESSU concept are based on its capacity to implement the following activities: describe, design, monitor, and model a wide range of intercropping and agroforestry systems that support TES. In the following sections, we define and describe the ESSU and its applications in a wide range of diversified agroecosystems using the ESSU concept to illustrate its value. We then discuss other uses of the concept such as supporting the design of experimental protocols, agroecosystem functioning models, optimized cropping systems, and as a monitoring and evaluation tool. We conclude by identifying the limits of ESSU.

2 The concept of ecosystem services functional spatial unit

2.1 Description

The ESSU definition given in the introduction relies on two propositions. First, diversified and multifunctional agroecosystems can be considered as the spatial repetition of elementary units, so that it is useful to delimit the smallest repeated spatial unit. Secondly, in agroforestry systems, we already know the ecosystem services provided by all the interacting species and other functional components. Following our definition, the same properties characterize an ESSU and the agroecosystem it is representing. When interactions are expected between two or more spatial units, such as when a TES is located between two spatial units, then these two spatial units are part of the same ESSU. The properties that the ESSU concept focuses on are plant and animal taxonomy (e.g., species names and varieties), plant and animal status in the agroecosystem (e.g., crops, service plants, weeds, biological pest controllers, and cattle), plant development in space and time (e.g., size, stratum, perennial or annual, and age), animal population dynamics for pest control, the plant spacing design, and the animal density per hectare. For these reasons, the ESSU is at a larger scale than the plant and animal but smaller than the field/farm/territory, with its scale determined by the largest TES provision area. The ESSU concept complements agronomists’ scale concepts (plant, stand, field, farm, and territory) and their technical concepts (plant techniques like pruning, technical management sequence, cropping system, farming system, farm functioning) that integrate the technical management at different scales (Doré et al. 2006). Specifically, the ESSU concept is both (i) a complementary scale for agronomists by providing the smallest spatial unit encompassing the spacing design of the species in their relative proportions in the agroecosystem; and (ii) a technical concept formalizing the technical management of species interactions that provide TES.

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In intercropping systems based on arable crops, Justes et al. (2021) show the links between field management practices (including inter-row and within-row spacing, location of uncultivated habitats) and harvesting strategies of main crops (separate harvests, full harvesting with direct use, and full harvesting with cleaning or sorting before use) for explaining different performance outcomes of intercropping. Consequently, the area where each TES is provided results from the choices of field management and harvesting strategies. Thus, the ESSU can change according to farmers' management decisions.

Diversified agroecosystems consisting of perennial crops may evolve over years or decades because the life cycle of perennials implies a succession of "young" (unproductive), "mature" (productive), and "senescent" (low production) stages. Also, farmers may change their cultural practices because of newly acquired knowledge and/or the progressive introduction of improved technologies. The life cycle changes of perennials can result in TES changing in stages or gradually. TES could change in steps through time punctuated with periods of stability. However, smallholder farmers typically rejuvenate old cocoa agroforestry systems gradually, often tree-by-tree, rather than rejuvenating their whole plot at one time (Jagoret et al. 2017). In both cases, an ESSU can accommodate different development stages in the same agroecosystem as well as accommodating changes in TES over time.

The concept of ESSU integrates the characteristics of the species mixtures interacting in and making use of the same space such as livestock, spontaneous below and aboveground flora/fauna, and their dynamic interactions over time. Depending on species architectures (above and belowground) and temporal development, the ESSU can be single-stratum or multi-strata. It includes the corresponding biotic and abiotic conditions, and interactions between species and other living organisms in the spatial unit. In agroecosystems managed by farmers, the composition of species and the spatial arrangement of plants or groups of the same plants in the plot and their temporal evolution are of fundamental significance for describing, analyzing, and representing the functions provided by the ecosystem. The concept of ESSU could pave the way to modeling both existing and newly designed intercropping and agroforestry systems more generally, by simplifying them into ESSU which provide sets of TES. When auditing the different TES provided by different agroecosystems or by transitioning agroecosystems, the ESSU concept could provide a relevant scale for comparisons.

2.2 How to identify and represent an ESSU?

The ESSU concept can be used to represent an elementary spatial unit of diversified agroecosystems to aid understanding of the functioning of actual systems by formalizing TES and spatial arrangements of species mixtures. Before studying its functioning, it is first necessary to identify the ESSU.

Identifying an ESSU requires identifying a set of desired ecosystem services to form the TES (not all ecosystem services will be desired and become part of the TES). Then, the TES are identified as well as the time scale and the species assemblage needed to provision these TES. The ESSU should represent the smallest spatial unit that includes all the species and the corresponding area required to provide the TES. The agroecosystem species spacing design determines TES provision areas. The ESSU encompasses these areas and all the species in their field relative proportions. To determine the ESSU area, we recommend starting with the TES provided by the species with the lowest density (e.g., shade trees in coffee or cocoa agroforestry systems, trees in alley cropping systems), once the relative field proportions of species are known. Indeed, the size of the ESSU depends on the largest TES provision area, often provided by the species with the lowest density.

In addition, the TES are mostly the outcome of interactions between species. Consequently, plant scales are usually irrelevant to describe TES provided by diversified agroecosystems because the plant scale does not take into account the distance between species. Yet, the area provisioning a particular TES can be smaller than the plot (e.g., a few square meters can provide the biomass production service). However, some TES can be provided only at a wider scale than the plot as the functions subtending them occur outside the plot as edge effects (e.g., biological regulation services linked to semi-natural habitats such as hedges, ditches, and forest patches). In such cases, the ESSU will encompass the semi-natural habitat and may be useful for landscape design, modeling, monitoring, or auditing (within one or more farms).

3 Application of the ESSU concept to describe a wide range of intercropping and agroforestry systems

To illustrate the general applicability of the ESSU concept, we apply it to a range of intercropping and agroforestry systems. We used the nomenclature proposed by Malézieux et al. (2009) to differentiate multispecific agroecosystems according to their composition of annual and/or perennial crops and their spatial organization.

3.1 Single stratum intercropping systems

Intercropping systems based on arable crops are single stratum diversified agroecosystems. For each of the four examples considered in Fig. 3, we identified an ESSU corresponding to a set of TES.

In single stratum cereal/legume mixtures, herbaceous legumes can be mixed with cereal plants, in the same row

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(Fig. 3a) or in alternate rows (Fig. 3b). In both cases, the same ecosystem services are commonly targeted (TES 1 and TES 2). As the interspecific interactions occur at the individual plant level or at the level of a few plants organized in a homogenous group, the whole plot can be considered as the repetition of one ESSU comprising a few rows. In the situation of mixed species within the row (Fig. 3a), it is convenient to set the ESSU as 1 m^2 of mixed species to avoid micro-spatial heterogeneity due to mechanical sowing, even if it could also be determined theoretically according to the plant density (e.g., one legume plant and four cereal plants). In the alternate rows situation (Fig. 3b), the ESSU can be set as 1 row of each species of 1 m length (also to avoid micro-spatial heterogeneity of inter-plant distance due to mechanical sowing).

Three types of ecosystem services (TES 3, TES 4, and TES 5) may be targeted from strip intercropping of two arable crops (e.g., soybean and sunflower) (Fig. 3c). However, the inter-specific interactions are occurring heterogeneously in the plant cover according to the spatial structure and the distance between rows of the species in combination with differences in their heights, which strongly determine light capture.

The alternate strips of crop and uncultivated grass (Fig. 3d) could be effective for reducing run-off, soil erosion, and surface water pollution on slopes. Indeed, grass strips are effective for reducing soil and pollutants transfer and for enhancing diversity in soils and vegetation by providing animal habitats. These TES can be summarized in two types: production (TES 6) and regulation (TES 7). The provision area of these TES is spatially dependent and consequently defines the limits of the ESSU.

3.2 Multi-strata agroforestry systems

Agroforestry systems can be analyzed according to their complexity in terms of species interactions over short distances in the same plot and according to their spatial geometry.

3.2.1 Coffee-based agroforestry systems

In simple coffee-based agroforestry systems, coffee trees are associated with a single species of service tree. For example, in Costa-Rica, the most popular associated species in coffee plantations is the leguminous *Erythrina poeppigiana* (Meylan et al. 2017). The ecological functions associated with *E. poeppigiana* are mainly related to soil nutrient availability by increasing total and inorganic N content, N

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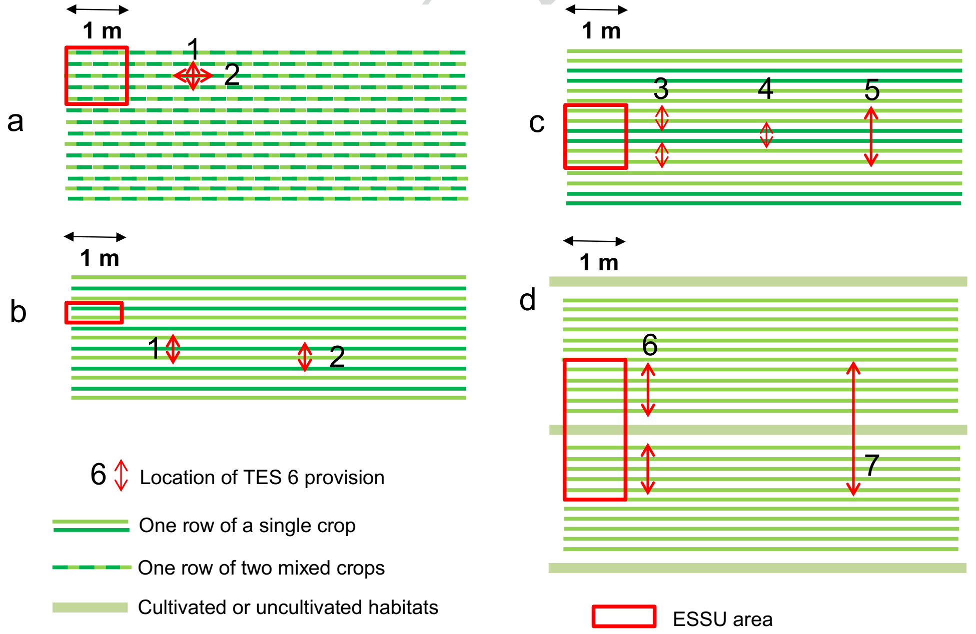

Fig. 3 Application of the ecosystem services functional spatial unit (ESSU) concept to four types of intercropping systems based on arable crops: (**a**) mixed crops in the same row; (**b**) mixed crops on alternate rows; (**c**) mixed crops on alternate alleys; (**d**) single crop in alley, alternating with uncropped strips. The red squares delimit ESSU; numbers label the targeted ecosystem services (TES); and red arrows show the spatial extent of each TES. TES 1, the cereal plants provide a physical support (stick effect) to the legume to prevent lodging. TES 2, niche complementarity for nitrogen resources where cereal is taking up only inorganic soil nitrogen while legumes increase N_2 fixation to maintain its nitrogen nutrition, thus enhancing yields. TES 3, sunflower grain production. TES 4, soybean production. TES 5, the barrier effect of sunflower limiting disease dispersion between soybean rows and also the modification of the microclimate due to the difference in height between the two associated crops. TES 6, annual crop production. TES 7, biological regulation.

mineralization, food web structure increasing nematode densities and detritivorous microarthropod densities (Sauvadet et al. 2018), and soil structure by increasing rainfall infiltration (Meylan et al. 2017). Moreover, shade provided by *E. poeppigiana* changes the microclimate, which has a direct impact on coffee pest and disease dispersion and development (Allinne et al. 2016; Avelino et al. 2018). Microclimate regulation (temperature, humidity, and radiation) also induces changes in coffee tree physiological development and yield component allocation (Charbonnier et al. 2017). All these biophysical mechanisms interact (Andres et al. 2016) to generate various ecosystem services at the *Erythrina* shade tree scale: two of regulation (pest and disease control, soil erosion); one of support (nutrient cycling); and one of provision (coffee yield).

In the example above from Costa Rica, the *E. poeppigiana* trees are at the center of all the TES provided at a large scale, while coffee production is a service provided at a much smaller scale: one coffee tree. Because each *E. poeppigiana* tree is surrounded by six others, the ESSU is hexagonal (Fig. 4a). The whole coffee plantation is therefore represented as a repetition of this basic ESSU.

E. poeppigiana pruning allows producers to regulate the intensity of TES 2 and 3 according to time-specific needs through the year. For example, heavy pruning increases the intensity of TES 3 and reduces the intensity of TES 2, which increases coffee flowering (Fig. 4b). In contrast, increased shade cover during coffee grain filling and maturation (Fig. 4a) regulates the sink-source relation in the coffee plant, reduces physiological dieback, and improves coffee quality (Vaast et al. 2006). The annual cycle of heavy pruning at coffee flowering followed by the increase of shade before maturation does not result in ESSU seasonal changes.

3.2.2 Agroforestry system of fruit or timber trees with arable or service crop in alleys

The example presented in Fig. 5a concerns orchards and vineyards with crops or service plants in the inter-rows.

The design of agroecosystems based on fruit trees in rows, together with low stratum service plants in the inter-row (e.g., cover plants, flower strips, legumes, and deep-rooted plants), provides various ecosystem services (Albert et al. 2017; Demestihas et al. 2017; Lauri and Simon 2019; Pitchers et al. 2021; Simon et al. 2017). In the inter-row, service plants enhance pollination and biocontrol by hosting predators or repelling plant enemies (e.g., *Rosmarinus officinalis*, *Tagetes patula* in temperate orchards, and *Musa* spp. in tropical cocoa-based plantations). They also provide supporting ecosystem services such as nitrogen cycling (e.g., by *Cajanus cajan*, *Desmodium intortum*, and *Phaseolus vulgaris* in cocoa and coffee-based plantations), and water cycle regulation, that includes water flow maintenance and water quality protection, both being tightly related to erosion control and

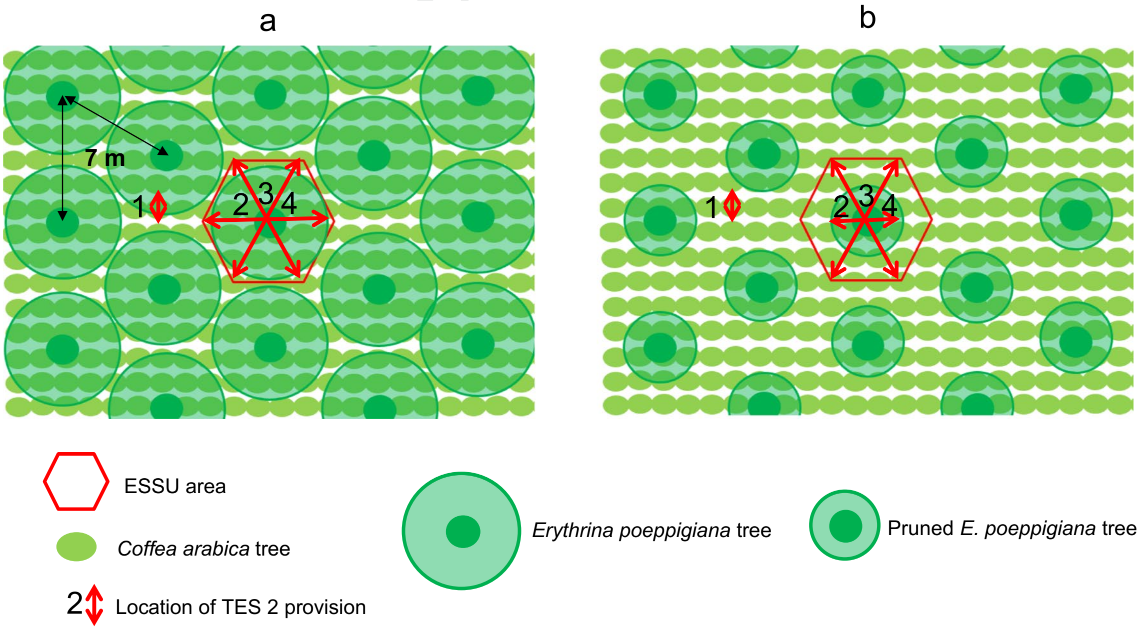

Fig. 4 Mature arabica agroforestry systems managed by smallholders in Costa-Rica: the targeted ecosystem services (TES) described in the text are all within the hexagonal ecosystem services functional spatial unit (ESSU). Heavy pruning at coffee flowering does not alter the ESSU. The red hexagon delimits ESSU; numbers label the TES; and red arrows show the spatial extent of each TES. TES 1, coffee production. TES 2, shade provision (its spatial extent changes after *E. poeppigiana* pruning). TES 3, soil mulching and soil nitrogen increase by pruned *E. poeppigiana* branches and leaf fall. TES 4, niche complementarity for soil (for coffee tree) and air (for *E. poeppigiana)* nitrogen.

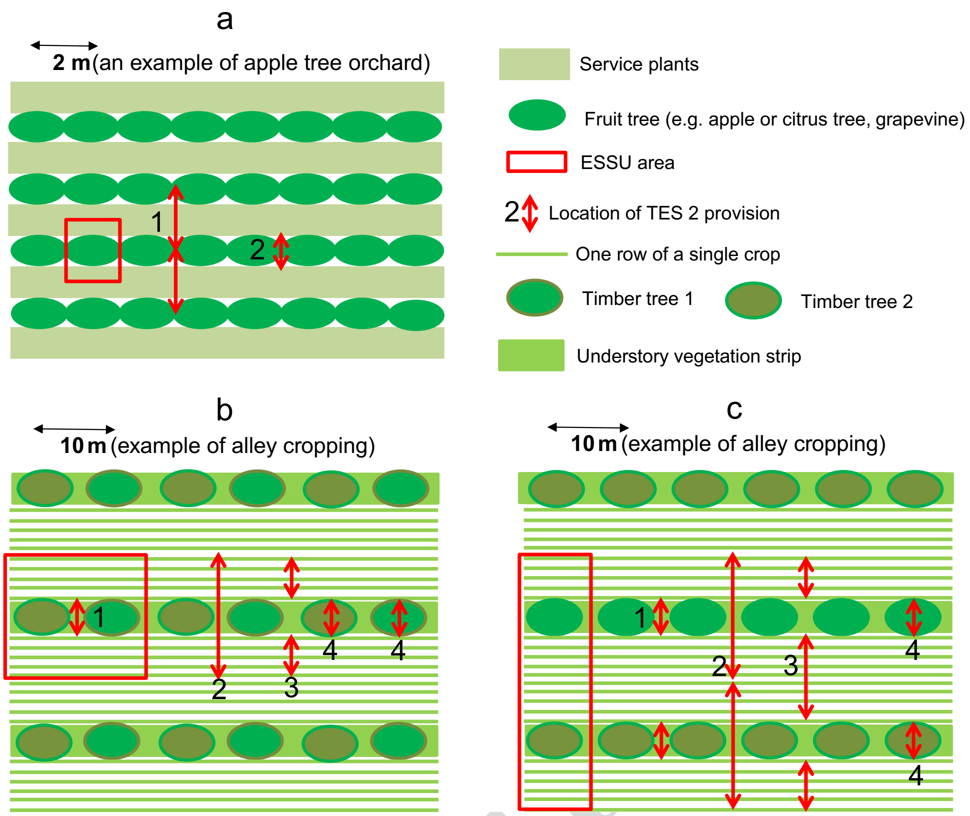

Fig. 5 **a** Application of the ecosystem services functional spatial unit (ESSU) concept in two-strata orchards where fruit trees (e.g., apple trees, citrus or grapevines) are in rows and service plants in inter-rows. The distance between trees in rows varies depending on the tree species and on the training system (e.g., from 1 m for grapevine, to 1–2 m for apple trees and 2–6 m for citrus). The red rectangles delimit ESSU; numbers label the targeted ecosystem services (TES); and red arrows show the spatial extent of each TES. TES 1, pollination enhancement, biocontrol, nitrogen cycling, and erosion control. TES 2, production. **b** and **c** Application of the ESSU concept in agroforestry systems associating arable crops and timber trees, and examples of associated ecosystem services. TES 1, natural habitats, carbon storage, in some cases food production (in cases where berry shrubs or aromatic herbs are planted). TES 2, natural biocontrol and microclimate modification. TES 3, arable crop production. TES 4, wood production.

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improved infiltration. In addition, fruit trees or vines provide a production service on the tree row. Consequently, the ESSU is defined as at least one fruit tree or vine together with the two adjacent half-alley sides, and the whole orchard or vineyard is conceptualized as the repetition of this basic ESSU.

Figure 5b and c presents examples of agroforestry systems based on alley-cropping (e.g., timber tree rows with spacing allowing mechanized production of the crops in the alleys between tree rows). Three types of vegetation strata can be identified, each one providing a TES: the high strata trees (main TES, wood production); the crop, possibly including medium strata trees (main TES, food or feed production); and the understory vegetation strip (main TES, refuge for plant diversity, natural habitats for beneficial arthropods, carbon storage; see Boinot et al. (2019)). Thus, the ESSU encompasses all three or more strata in their respective densities, and contains the whole gradient of interactions between the three elements. Due to the potential anisotropies in these interactions (e.g., with east-west tree rows, the crop in the north part of the crop alley experiences different growing conditions to the crop in the south part of the alley; Inurreta-Aguirre et al. 2018), the ESSU also encompasses both alley half-sides of the tree row. With a single species of timber tree, the ESSU encompasses only one tree. If several timber species are mixed within the tree row, the ESSU extends to encompass all the tree species along one line to reflect the same relative densities of each tree species along the whole line (Fig. 5b). If different species of trees are planted over different lines (Fig. 5c), the ESSU encompasses several tree rows in the same frequency as in the whole plot.

3.2.3 Highly diversified multi-strata agroforestry systems

In small Pacific islands such as the Vanuatu archipelago, traditional Melanesian food gardens are highly diversified agroecosystems. They are characterized by a high diversity of food crop species (short-cycle crops like maize and

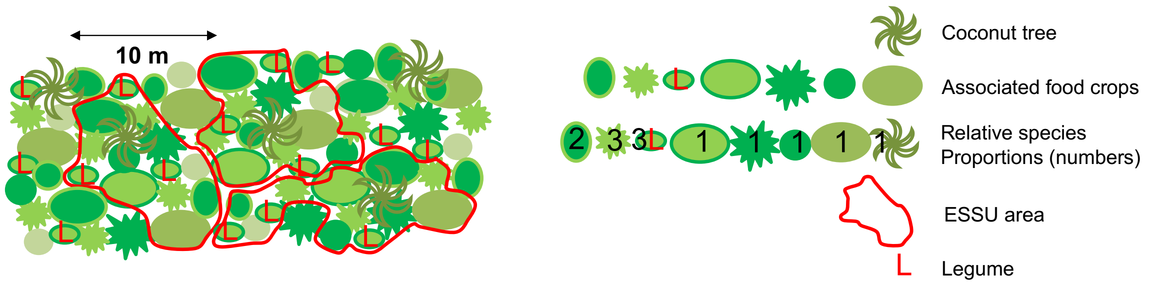

Fig. 6 The ecosystem services functional spatial unit (ESSU) concept also applies to highly diversified multi-strata agroforestry systems associating irregularly spaced short and long-cycle food crops, such as traditional Melanesian food gardens. The red lines demarcate ESSU boundaries. All targeted ecosystem services: food crop production and complementary access to resources.

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peanuts and longer-cycle crops like tubers, scattered plantains and pawpaw trees, and often bordered with coconut palms), irregular spacing, no fallow period, no fertilizer, plant scale rotation of species, and fertile volcanic soils (Vergara and Nair 1985; Clarke and Thaman 1993). Commonly, TES may be production and complementary uses of space and resources during the different phases of the cropping cycles. By focusing on a qualitative approach to ecosystem services provision when designing the ESSU, an exhaustive description of all different component species and their spatial arrangement is not necessary. Instead, species can be grouped according to the functions they perform, in order to simplify the representation of the spatial arrangements. Due to the irregular spacing of the different cultivated species in the field, the boundaries of the corresponding ESSU have an irregular shape (Fig. 6).

3.2.4 Highlights of Section 4

We highlight the transversal rules to define the ESSU in different agroecosystems. ESSU boundaries depend mainly on the species that provides the TES with the largest provision area. Regular spacing leads to a polygonal shape of ESSU; square or rectangular spacing leads to an ESSU with square or rectangular shape (Fig. 3a, 3b, 3c, 3d, 5a, 5b, 5c); and triangular spacing of shading trees (Fig. 4) leads to an hexagonal ESSU shape (Table 1). In contrast, irregular spacing leads to an irregularly shaped ESSU (Fig. 6).

The ESSU always encompasses all the TES and the smallest number of each species in its relative field proportion, even with irregular spacing (Fig 6). For species planted in rows as a single crop (Fig. 3b, 3c, 3d, 4, 5a, 5c), the ESSU must encompass the smallest number of rows repeated as a regular pattern (Table 2). When arable crops are mixed on the row (Fig. 3a), the ESSU length on the row is a 1 m standard while for tree crops it is the smallest number of trees repeated as a regular pattern on the row (Fig. 5b).

4 Use of the ESSU concept

In this section, we show how the ESSU concept could be used for auditing ecosystem services provision in agroecosystems, for modeling and designing intercropping and agroforestry systems.

4.1 Auditing ecosystem services provision in diversified agroecosystems

4.1.1 The ESSU concept: an appropriate scale for auditing ecosystem services provision

Complex systems raise the question of how they can be characterized, described, and compared for auditing ecosystem service provision by different agroecosystems. In the case of heterogeneity induced by the structure of the vegetation association, the ESSU makes it possible to identify the smallest scale at which it is appropriate to measure variables for cropping system analyses and construct assessment indicators (see Masure et al. 2022 for how this concept was used to review oil palm agroforestry systems worldwide).

Metrics can be established for the different components of the ESSU such as crops, soils, weeds, and pests. To specify the sampling within the ESSU, several metrics can be developed: functional traits, images, and inventories, all of which are spatially explicit, according to the description of the ESSU. Such metrics are linked to the processes determining the TES and can be mobilized for the monitoring

Table 1 Common principles for defining the boundary shape of ecosystem services functional spatial units (ESSU) based on spacing type

Type of spacing design	Shape of spacing design	ESSU boundary shape
Regular spacing	Square or rectangular	Square or rectangular
Regular spacing	Triangle	Hexagonal
Irregular spacing	Irregular	Irregular

Table 2 Common principles for determining the size of ecosystem services functional spatial units (ESSU) based on the spacing design of the different component species

Type of spacing design	Design on the row	Component crops	ESSU encompasses
Regular spacing	Rows of single crop	Tree crops	The smallest number of rows repeated as a regular pattern and the smallest plant number of each species in its relative field proportion
Regular spacing	Rows of single crop	Arable crops	The smallest number of rows repeated as a regular pattern and 1 m standard length on the row
Regular spacing	Crops mixed on the row	Tree crops	The smallest number of trees repeated as a regular pattern on the row and in between rows, and other species in their relative field proportions
Regular spacing	Crops mixed on the row	Arable crops	1 m standard width and length
Irregular spacing	No row	All crops	The smallest plant number of each species in its relative field proportion

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and management of the ESSU over time. For example, the green manure TES can be both assessed and managed by determining the service crop biomass: once the service crop biomass target is reached, the service crop can be destroyed and returned to the ground to provide the green manure TES.

The ESSU concept can provide a rapid and standardized tool for auditing ecosystem service provision across agroforestry systems, and can also indirectly help the development of analytical tools, representations, and indicators useful for auditing. The concept facilitates easy comparisons of the provided TES across different agroforestry systems and enables determination of the diversity and frequency of the TES provided, all important for auditing ecosystem services provision. This capacity to audit ecosystem services provision and monitor their change in response to development interventions is becoming increasingly important in the context of the UN's Sustainable Development Goal 2, AQ3 Target 2.4 (see Section 2). ESSU is a tool for establishing baselines in ecosystem service provision and for assessing progress towards Target 2.4 in terms of improved resilience of agricultural systems and strengthened adaptive capacity.

4.2 The ESSU concept: a tool to assess the spatial gradient of TES provision

The intensity of TES provision was spatially homogeneous in all the cases presented in Section 4. Nonetheless, many ecological "processes" show spatial variability by species and agroecological infrastructure (e.g., shade intensity varies spatially with canopy density and shelter varies with distance from tree hedges). We describe in this section how the ESSU concept could represent a spatial gradient of biological control of pests at the landscape scale.

Figure 7 is a hypothetical area of farmland that includes strips of uncultivated habitats and a complex field margin that generates edge effects. This field margin is L-shaped and separates three fields: one vineyard and two fields of mixed annual crops. In such landscapes, the ESSU concept can illustrate how the farmer manages biological control of pests according to distance from agroecological infrastructures.

In addition to the grape production service (Fig. 7; TES 1) in the vineyard, maintaining spontaneous (or sowing) selected service crops in grapevine inter-rows can provide multiple ecosystem services (Garcia et al. 2018). Here, we provide examples of three different TES: erosion reduction (Fig. 7; TES 2); soil fertility improvement from green manure (Fig. 7; TES 3); and biological control of pests (Fig. 7; TES 4). Erosion occurs mainly in grapevine inter-rows as preferential corridors for water runoff (García-Ruiz 2010). Moreover, technical management of inter-rows is the main lever to reduce water runoff and soil erosion in vineyards, and partially depends on the composition of inter-row plant communities and their functional structure (e.g., Garcia-Ruiz et al. 2010). Consequently, it is appropri- AQ4 ate to limit the scope of the erosion reduction TES to the inter-row scale. The soil fertility improvement TES may involve the grapevine row, as the manure is anticipated to improve production of the main crop. Here, the inter-row management may be the main lever to improve soil fertility with service crops like cover crops, but some species that grow in the grapevine row may compete with grapevines for soil nutrients. Therefore, the appropriate provision area for soil fertility improvement from green manure TES would include a vineyard row and the two adjacent half-inter-rows.

The provision area for the biological control of pests TES includes the vineyard's surrounding vegetation (Fig. 7; complex field margin), because species diversity is determined both by service crops inside the field (e.g., Burgio et al. 2016) and habitats outside the field (Landis et al. 2000; Rusch et al. 2016). Distance from agroecological infrastructures (edge effects) is also important for the level of biological control of pests by insects or other animals (e.g., Thomson and Hoffmann 2013). In Fig. 7 example, we represent a situation where the provision area for the biological control of pests is gradually decreasing from the agroecological infrastructure and limited to six rows. This gradient of biological regulation provision area can be adjusted to the population dynamics of the species controlling the pests. The ESSU corresponding to the set of TESs 1 to 4 is a rectangle

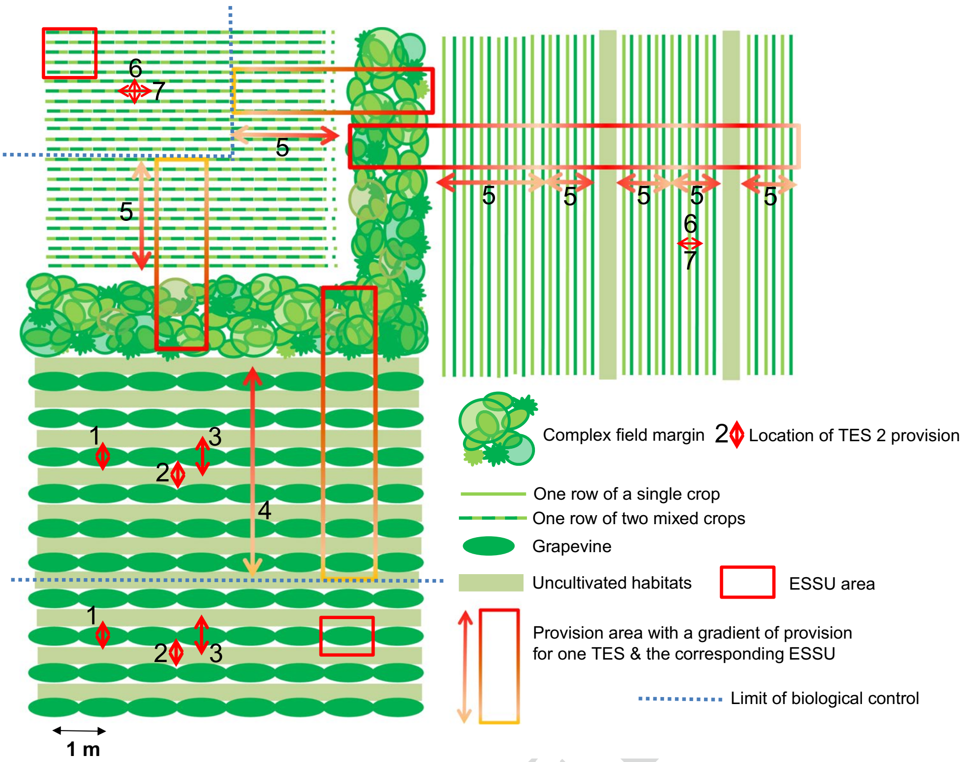

Fig. 7 In this hypothetical area of farmland, the different ecosystem services functional spatial units (ESSU) show the effects of the agroecological infrastructures (a complex field margin and strips of uncultivated habitats) on biological control of pests by insects and other animals, at the field and landscape levels. The different ESSU illustrate (1) the limits of the areas with biological control; and (2) the gradient of biological control. The red polygons delineate ESSU; numbers label the targeted ecosystem services (TES); and red arrows show the spatial extent of each TES. When there is a spatial gradient of TES provisioning, the red arrows and polygons are colored with a gradient from red to yellow (intense to weak). TES 1, grape production. TES 2, erosion reduction. TES 3, soil fertility improvement. TES 4, biological control of vine pests. TES 5, biological control of annual crop pests. TES 6, annual crop production. TES 7, niche complementarity for nitrogen resources.

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as long as the width of six adjacent rows and inter-rows and as wide as one grapevine stock. Outside of the provision area of the biological control of pests, the ESSU corresponding to TES 1 to 3 encompasses only one grapevine and half of the surrounding inter-rows.

Similarly, in the field of annual crops mixed in the row, the provision area for the TES of biological control of pests (Fig. 7; TES 5) is limited to a specified distance from the complex field margin (e.g., Boinot et al. 2019; Cordeau et al. 2012). Its extent determines the shape of the ESSU for this part of the field, including the TES provision area for annual crops production (Fig. 7; TES 6) and niche complementarity for nitrogen resources (Fig. 7; TES 7). In the field of annual crops sown in strip intercropping, both the complex field margin and the strips of uncultivated habitats provide complementary and independent gradients of biological control of pests. The uncultivated strips are optimally located in relation to the field margin and from each other to provide some level of biological control of pests everywhere in the field (Fig. 7 TES 5). In this field, the ESSU gathering TES 5 to 7 is 1m wide and encompasses the complex field margin, all the rows of single crop and both strips of uncultivated habitats.

Integrating surrounding agroecological infrastructures such as windbreaks, hedges, riparian forest, and riparian buffer strips (i) enables scaling-up of the ESSU; and (ii) implies choosing a threshold for provision of biological control of pests by insects and other animals. More generally, we illustrate that the ESSU concept is (i) applicable from the plant to the landscape scale and (ii) accommodates spatial gradients of intensity of provision of particular TES. When juxtaposed ESSU are identified at the landscape level, there is no interaction between them by definition (Fig. 7). If an interaction is perceived between two ESSU, then they are not correctly identified.

4.2.1 The ESSU concept: a tool for auditing TES provision during the evolutionary path of an agroecosystem

While an ESSU figure at a given time represents the species spatial arrangements and the TES they provide, several ESSU figures can represent the evolutionary path of an agroecosystem.

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For example, we identified three steps within the life cycle of a smallholder's oil palm plantation grazed by cattle (Fig. 8).

Step 1: Intercropping juvenile oil palm. Smallholders intercrop juvenile palms with food crops. Some of them sow *Pueraria javanica* as a legume cover-crop after the food crops are harvested; others let weeds grow. If food crop spacing is irregular (like in Fig. 8, step 1), then the ESSU has an irregular shape delineated by a representative assembly of intercropped food crop species around one juvenile palm. This step ends when the cover of the cover crop/weeds takes over the food crops cover.

Step 2: Short stature mature oil palm plantation. During this step, oil palm comes into production and the expanding oil palm canopy prevents food gardening. There is still enough light for a sown cover-crop or weeds to cover the ground. The triangular spacing of palms leads to a hexagonally shaped ESSU.

Step 3: Tall mature oil palm plantation. This step starts when the palms are tall enough to prevent physical damage from large animals. Then, cattle are introduced and graze on either sown cover crops or weeds, and they fertilize the soil with manure. The ESSU then covers the provision area of both the TES for feeding one animal and the TES for fertilization by cattle manure.

This example illustrates how the ESSU concept can (i) represent the evolution through time of diversified cropping systems; and (ii) audit the ecosystem services provided during evolutionary paths of agroecosystems.

4.2.2 The ESSU concept: a tool for comparing different pathways in transitioning agroecosystems

Farmers choose different pathways and strategies when transitioning from one agroecosystem to another. This is the case in Central Cameroon, where the perennial grass, *Imperata cylindrica*, is a major barrier to the establishment of cocoa on savannah land. Farmers have developed two successful strategies to eliminate this grass (Jagoret et al 2012). The first strategy, which is more labor efficient but has less potential for food gardening during the transition phase, consists of hand-sowing oil palm at high density (ca. 1200 individuals ha^{-1}) to create a dense shade that eliminates *I. cylindrica* within four to 5 years. Then, farmers reduce the density of palms (to less than 100/ha^{-1}), and use felled palms to produce palm wine. They also introduce cocoa and fruit trees and retain some self-seeded forest trees as shade for the developing cocoa. The second strategy, which is more labor-intensive but provides more land for food gardening in the transition phase, utilizes annual food crops. Farmers carry out a deep manual ploughing and then successively sow some short-cycle species (peanuts, cucumbers, maize, etc.). Ploughed rhizomes of *I. cylindrica* are exposed to sunlight and rapidly dry out. After two or 3 years of cultivation,

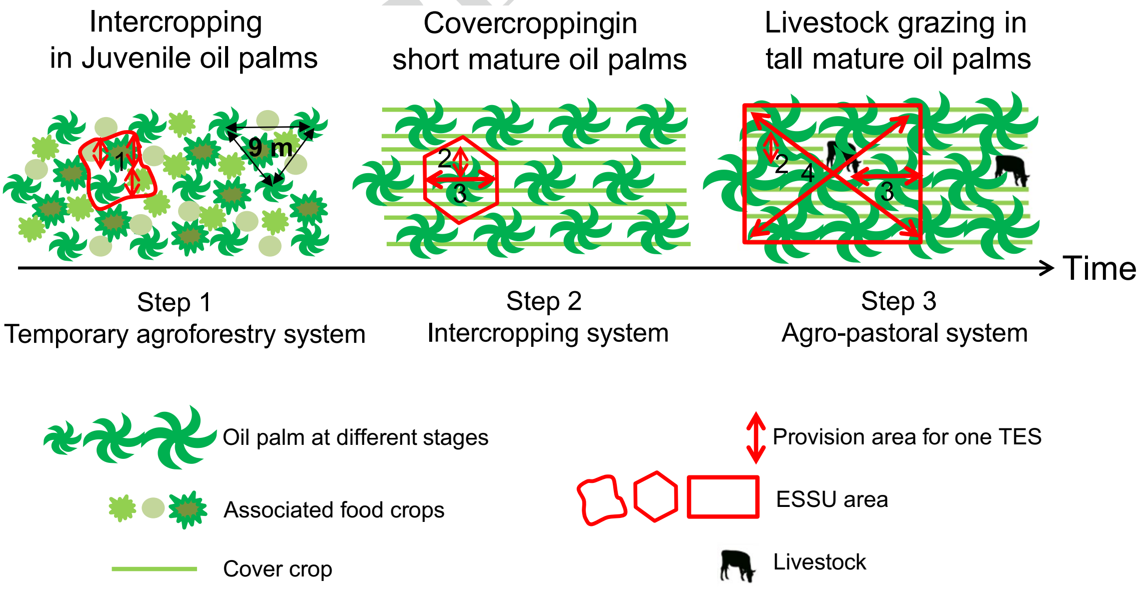

Fig. 8 Analysis of the evolution of a diversified oil palm cropping system in Cameroon over three decades. The services functional spatial unit (ESSU) evolves in three steps from juvenile palms (step 1) to short stature mature palms (step 2) and then to diversification with animals (step 3). The red lines delimit ESSU; numbers label the targeted ecosystem services (TES); and red arrows show the spatial extent of each TES. TES 1, food crop production. TES 2, niche complementarity for nitrogen resources between cover crop and palms. TES 3, oil palm fruit production. TES 4, animal feed and manure.

farmers introduce cocoa and fruit trees while retaining some self-seeded forest trees.

Under both strategies, the cocoa agroforestry systems initially established on savannah mature and become like agroforestry systems initially established on partially cleared forest (Fig. 9). While aging, these cocoa agroforestry systems lose some of their associated perennials either due to shade control or to senescence. For both transition strategies, the cocoa trees are managed in a similar way to cocoa systems that are initially established on partially cleared forest (Jagoret et al. 2018). Thirty to 70 years after establishment, they also reach similar provision levels of most TES (Nijmeijer et al. 2019). These two strategies underline the different phases through which these long-lived agroforestry systems can develop. In the first strategy, the very dense oil palm stand provides the TES of elimination of *I. cylindrica*, and later, the TES of palm wine production; while in the second strategy, successive deep ploughing eliminates *I. cylindrica* by manual labor, and the production of food crops is the TES.

The ESSU changes when the species cover and design change, providing other TES. Mobilizing the ESSU concept allowed comparison of the pathways for transitioning agroecosystem strategies from savannah to cocoa-based agroforestry systems.

4.3 Modeling diversified agroecosystems using the ESSU concept

4.3.1 Why is ESSU a useful concept for modelers?

Modeling is the conceptualization and representation of a phenomenon, process, or complex system in mathematical terms, which can then be implemented by numerical code in software algorithms. Modeling is widely used in agronomy to represent the cropping system functioning and predict

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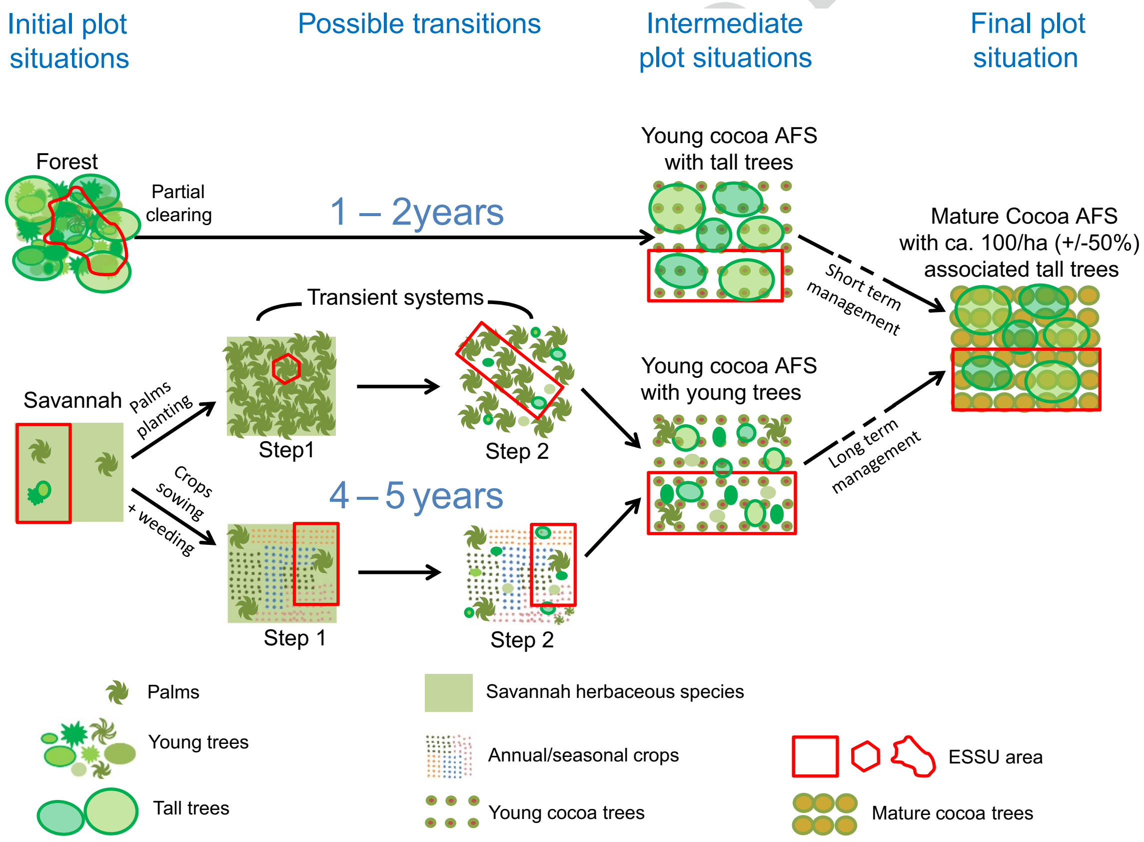

Fig. 9 Possible transition trajectories from forest or savannah to a mature cocoa-based agroforestry system (AFS). In forest, farmers hunt and gather irregularly spaced forest products; thus, the ecosystem services functional spatial unit (ESSU) has an irregular shape. In savannah, farmers produce annual food crops using a fallow rotation and harvest oil palm fruit; thus, the ESSU must integrate the few perennial crops. Following the oil palm transient system from Savannah to a young cocoa AFS, the first step utilizing high-density oil palms leads to a hexagonal ESSU around a single palm and eliminating the *Imperata cylindrica* by overshading. In the second step, farmers introduce young trees encompassed in the ESSU. Following the food crop transient system, the ESSU encompasses the diversity of food crops, the palms, and the young trees in the second step. In both young cocoa AFS and the mature cocoa AFS, the ESSU encompasses the cocoa trees and the shade trees according to their distribution, with a regular design. The red lines demarcate the ESSU.

yields and other plant/environmental variables for cropping, intercropping, and agroforestry systems, under the influence of various environmental conditions and technical management practices (e.g., fertilization, irrigation, and tree pruning).

Models should be as simple as possible, yet provide a meaningful representation of reality. However, the spatial distribution of different species is of major importance for species interaction and environmental services in diversified agroecosystems (Anderson and Sinclair 1993; Jose et al. 2004). In this context, the ESSU concept is useful as it helps identify the smallest spatial area characterizing the heterogeneous distribution of plants and their interactions in diverse agroecosystems (Gaudio et al. 2019). In spatially explicit models, edge effects are usually accommodated by defining boundary conditions, that is, deciding what happens when something (a particle, or, in the case of crop models, a plant organ, pest propagule, or tree shadow) reaches the edge of the simulated spatial domain. There are three types of boundary conditions: (i) periodic (what goes across the right border comes back across the left border); (ii) reflective (everything "bounces back" when reaching the border); and (iii) absorbing (things disappear when they go outside the simulated area). Periodic boundary conditions simulate infinite space, as if the patterns in the simulated area were repeated in all directions like a tiled surface. The ESSU, being an individual tile in a tiled space, should be modeled using periodic boundary conditions. For square (e.g., Fig. 3a), rectangular (e.g., Fig 5a), or hexagonal (e.g., Fig 4) ESSU, defining periodic boundaries is straightforward. For an irregularly shaped ESSU (e.g., Fig. 6), the modelers have to reshape the ESSU into a regular shape, keeping not only the composition (i.e., the proportion of each species), but also, as much as possible, the configuration (both in topological terms, that is, the connections between neighboring species and in terms of distances between species). This allows the whole space to be represented as a juxtaposition of the modeled ESSU (Fig. 10).

Thus, the ESSU concept should be a familiar and useful concept for modelers, as they have been using it for years—see examples below—without having a single term to name it. In this respect, using a common name for the ESSU concept might enhance communications, interactions, and synergies between field scientists (agronomists, *sensu lato*, and ecologists) and computer modelers, studying vegetation dynamics and field trial design.

4.3.2 Examples of model spatial domain definition using the ESSU concept

Hi-sAFe is a 3D agroforestry model for representing tree-crop interactions and their effects on some ecosystem services and dis-services. These include tree and crop production (taking into account tree-crop competition for light, water, and nitrogen) and regulation of groundwater quality (of the water cycle, of crop temperature, etc.) (Dupraz et al. 2019). To represent the simulated area (called the "scene"), the model can use absorbing and/or periodic boundary conditions on the different borders: an infinite agroforestry system (periodic boundary conditions on all sides); a forest or agroforestry field edge (one side with absorbing conditions); or a hedgerow (two opposite sides with absorbing conditions). Although the scene can theoretically be of any size and contain any number of trees, the smaller it is, the shorter the computation time. For the representation to be practical, the scene should thus not exceed the areal extent of the ESSU. In the simplest case—an alley cropping agroforestry plot, made of a single tree species of uniform age and size,

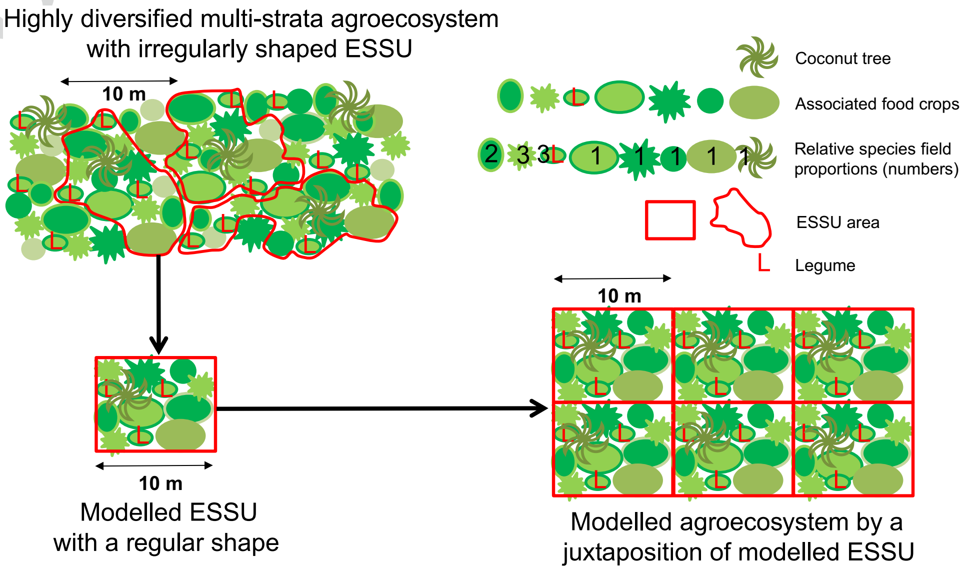

Fig. 10 For modeling purposes, irregularly shaped ecosystem services functional spatial unit (ESSU), as in Fig. 6, can be reshaped to have a regular shape adequate for modeling (square, rectangle, or hexagon).

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regularly spaced in a rectangular pattern—the scene should encompass one tree and have the same width and length as the within-row and between-row tree spacing, respectively (Fig 5b). An example of use of hi-sAfe, with such a rectangular ESSU, is the analysis of crop stress regulation and production made by Reyes et al. (2021). In the case where two or more species are mixed within the row, or tree management differs between trees (e.g., thinning of trees after some years), the scene must encompass enough trees so that all species and management regimes are represented in the correct proportions and the topology of trees is conserved. Thus, if the two species are planted in a square pattern, then the scene can contain two trees, but if each tree species is planted in a diamond shape, then the scene must contain four trees (Fig. 11).

The WaNuLCAS model is a soil-crop 2D model developed for simulating water, nitrogen, and light interactions in agroforestry systems (Van Noordwijk and Lusiana 1999; Van Noordwijk et al. 2011). The model was developed to deal with a wide range of agroforestry systems: hedgerow intercropping on flat or sloping land and fallow-crop mosaics or isolated trees in parklands, with minimum parameter adjustments. WaNuLCAS allows simulation of three plants (crop or tree) interacting together in a scene, which is the unit of simulation. As the scene is limited to three plants, complex agroforestry systems, containing more than three species, cannot be represented solely based on the real spatial configuration of all of them. In this case, again, the concept of ESSU is useful to modelers: (i) to simplify the system by grouping species (see Section 4.2.3); and (ii) to choose the species according to the target ecosystem service(s) under study.

The STICS soil-crop 1D model was initially developed for single crops (Brisson et al. 2008) and it was adapted to intercropping for simulating bi-specific alternate row intercropping systems organized in a simple spatial pattern (Brisson et al. 2004; Vezy et al. 2022). Here again, the modelers used the ESSU concept without naming it specifically. Indeed, they considered that the most important interaction between species was light competition (driving the services of crop production and temperature regulation), and defined the scene as the ESSU for these TES. The ESSU corresponds to the two species represented by half the canopy of one species, a half-canopy of the other species, and the inter-row distance between them. Other spatial aspects were neglected (e.g., spatial niche complementarity between rooting patterns of species).

4.4 Designing diversified agroecosystems

The ESSU concept can also be used as a generic tool for designing intercropping systems with farmers. When designing intercropping systems, agronomists are used to considering various key components simultaneously: field and machinery constraints, the TES, the species, and their spatial and temporal arrangements (Bedoussac et al. 2015; Justes et al. 2021; Stomph et al. 2020). Thus, they are familiar with some aspects of the ESSU concept. For agronomists, the novel part of the concept is that the ESSU is based on the smallest spatial unit to be designed to represent the system. On the basis of how we have planned to design agroecosystems in several ongoing projects, we formulate hypotheses on the questions that a designer would have to consider to use the ESSU concept during a design process. As a result, we suggest the following four steps for designing diversified agroecosystems. The three steps design process proposed by Gaba et al. (2015) for developing sustainable multiple cropping systems are included in steps 2 and 3 of our proposition.

Step 1: Consider all constraints and available means for managing the future agroecosystem according to the farmer's production objectives, both at the farm and at the plot scales. The farm structure, labor availabilities, and the machinery for both the field management practices and the post-harvest product transformation must be considered in the design of the spatial arrangement within the plot (Meynard 2012; Simon et al. 2017). For example, combine harvester and sprayer widths are key factors influencing the spatial design of timber tree rows inside arable plots (Dupraz and Liagre 2008).

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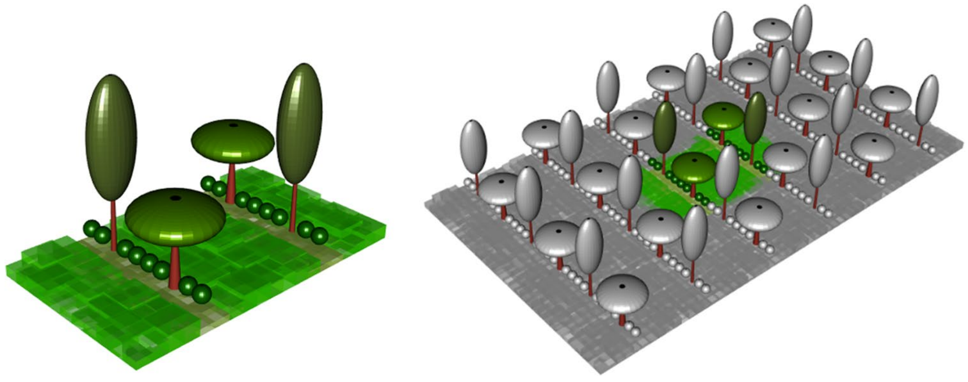

Fig. 11 An example of a Hi-sAFe scene with two tree species planted in a diamond pattern (with shrubs on the tree row), and the corresponding plot obtained with periodic boundary conditions: the central pattern in color is the ecosystem services functional spatial unit (ESSU), while the rest of the plot (in gray) is a spatial replication of the ESSU like a mosaic of tiles.

Step 2: Determine the set of TES to be considered. The ESSU is defined with regard to the provision of a set of TES provided simultaneously or successively during the different phases of the intercropping system, according to the farmer's objectives and local environment. For example, farmers currently design most cocoa-based agroforestry systems in the Caribbean (Notaro et al. 2020; 2021; 2022) by first targeting ecosystem services relying on the provision of annual crops and plantains, as well as soil fertility improvement during the unproductive phase of the cocoa tree. As soon as the cocoa tree canopy closes and the first pods are being produced, the farmer will cease annual cropping and gradually reduce plantain production while new TES are included, such as cocoa and fruit production, as well as new management techniques for pests, diseases, and pollinating insects.

Step 3: Identify requirements for species diversity and spatio-temporal structures to provide the TES. The diversity of cropped species and their spatial arrangement is of crucial importance for the provision of TES. The spatial arrangement (distances between plants) and topology should take account of the interactions between species. This is to minimize adverse effects such as allelopathy and competition for resources, and to increase positive effects like pest deterrence and improved water infiltration. The management of the plot through time must also be considered for agroforestry systems. It should take into account the evolution of inter- and intraspecific interactions such as rising tree-crop competition with tree age. In the most abstract approach, a TES can be defined without referring to particular species by using functional traits. Translation of the prototypal ESSU into practical implementation such as selection of species and cultivars and precise mapping of the plot can be done afterwards.

Step 4: Determine the ESSU and replicate it throughout the plot area. By relying on existing knowledge of plant interactions, an ESSU can be designed for each development phase of the agroecosystem and its corresponding TES. The ESSU can be drawn as the simplest selection of interacting plants (various species) and habitats capable of providing the set of TES, in space and time. Then, the ESSU can be modified to accommodate changing farming strategies or agroecosystem structures, for example, in relation to tree growth.

4.4.1 Highlights of Section 5

- The ESSU concept is an appropriate scale for auditing TES because of its practical usefulness to represent, describe, and compare the provision of TES in agroecosystems. Delimiting an ESSU may be useful for shaping a sampling strategy within a diversified agroecosystem to assess the provision of a given set of TES.
- At farm and landscape levels, it is also a tool to assess the spatial gradient of the TES' provision intensity, such as biological control of pests.
- We used it as a tool to represent the different steps of the evolutionary path of an agroecosystem and to compare different pathways in transitioning agroecosystems. We found it useful to describe the changes in the management of crops, in crop succession or in farmers' changing production strategies and priorities. This concept allows simple representations of evolution in the TES provided by an agroecosystem. It allows consideration of the trade-offs between TES associated with different strategies of agroforestry transition and other contextual factors like land pressure and smallholder labor availability.
- Delimiting an ESSU also permits a reduction in the complexity when modeling TES provision by agroforestry or intercropping systems. The concept is compatible with the formalisms of Hi-sAFe 3D, WaNuLCAS 2D, and STICS 1D soil-crop models, notably for scene and boundary definition. The ESSU concept should be a familiar and useful concept for modelers, as they have been using it for years without having a single term to name it.
- Delimiting and replicating an ESSU can also be key final steps for designing a diversified agroecosystem. This would be done when all constraints, resources, and ecological processes have been identified and farmers' objectives have been reformulated as a set of TES. When designing cropping systems, agronomists are accustomed to considering the defining elements of the ESSU concept; what would be new to them is that its design is based on the smallest spatial unit possible.

5 Novelty, genericity, and limits of the ESSU concept

The ESSU concept relies on the two propositions presented in Section 3. Concerning the first proposition, we showed in Section 4 that for a wide range of diversified agroecosystems, each agroecosystem can be represented as a repetition in space of the ESSU, constituting the smallest spatial unit encompassing all the species and the TES provided. In Section 5, we explained that because the ESSU represented all the same TES as the agroecosystem it reflected, it could therefore be used for designing, modeling, or auditing agroecosystems. Concerning our second proposition that we already know, the ecosystem services provided by interacting species and other functional components demonstrate that our concept builds on an extensive literature about ecosystem services provided in intercropping and agroforestry systems (see, for example, the special issue of papers from around the world on the ecosystem services

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and environmental benefits provided by agroforestry—Jose 2009).

The ESSU concept sits at the interface between the knowledge on TES in diversified agroecosystems and the available frameworks (e.g., ecosystem service cascade framework presented in Fig. 2; Alam et al. (2014) framework), while being useful for existing intercrop and agroforestry models (Section 5.3.2). Daryanto et al. (2020) identified significant knowledge gaps regarding multiple aspects of intercropping, including examination of the effects of different crop combinations on ecosystem services. Our concept enables the ecosystem effects of different crop combinations to be explored. Furthermore, in a review article about European agroforestry, Fagerholm et al. (2016) highlight that research on the linkages between agroforestry and ecosystem services have not been fully explored, suggesting a need for stronger consideration of stakeholder participation to define, map, value, and foster ecosystem services. Because our concept builds graphic representations of the TES provided (Masure et al. 2022), it could offer an effective method, based on well-identified methodological steps, for assisting stakeholders through visualizing the provision area of the TES. Similarly, Juventia et al. (2022) propose a novel framework using graphic representation to include spatio-temporal aspects of strip cropping system design. This framework dedicated to strip cropping systems represents the rotations at the strip scale in the cropping system. It complements the more generic ESSU concept representing the TES and the species arrangements at ESSU scale, in all diversified agroecosystems. Both are conceptual tools addressing the call by Duru et al. (2015) for learning-support tools for the generation of knowledge about relations among practices, biodiversity, and associated ecosystem services for adaptive management.

5.1 Novelty of the ESSU concept

Agroecology thinking constitutes a significant break from "traditional" post-green revolution agronomy concepts in several aspects. Diversified agroecosystems are more complex and have more TES than existing widespread single-crop systems, based essentially on the single TES of crop production. Indeed, introduced biodiversity "complexifies" agroecosystem analysis, management, and assessment (Duru et al. 2015; Merot and Wery 2017). This is because the inputs oriented to each biophysical compartment are considered separately and each species is considered independently from others in terms of ecosystem service provision and spatial organization. Because of this complexity, the management unit cannot be defined at the field plot level as done in the "cropping system" framework. In this respect, the ESSU brings a robust strategy to recognize that multiple functions are managed simultaneously for multiple TES, and that diversity patterns within a field plot determine them. They define a new scale of analysis and management between the levels of plant and plot. By doing so, ESSU also highlights the idea that spatio-temporal patterns of organisms are essential components of diversity in the functioning of agroecosystems. Thus, the ESSU concept offers an effective method for accommodating complexity.

The areal extent of ESSU is not necessarily limited to the scale of cropping systems because ESSU can be defined at the "landscape" scale (*sensu lato*). This can include several cropping systems and elements that have been historically excluded from the management scope of agronomy like field margins, hedgerows, and surrounding natural habitats. In addition, ESSU can extend beyond short-term crop successions and deal explicitly with long-term trajectories of change of agroecosystems. The proposed ESSU concept extends the boundaries of agronomic concepts and scales (e.g., plant, plot, farm) and proposes a modular framework able to accommodate diverse spatial and temporal scales which is not easy with input-based approaches. As anticipated by Duru et al. (2015), the ESSU concept could increase attention on ecological functions and raise new research questions, not only for agronomy or agroecology, but also in soil and water sciences, animal ecology, landscape ecology, and human geography.

5.2 Generalizability of the ESSU concept

The ESSU concept can be applied across a broad range of agroecosystem types. We demonstrated its usefulness for comparative analyses, modeling work, and presented a four-step methodology for formalizing the design of complex agroecosystems such as intercropping and agroforestry. Because ESSU represents the link between the structure and the functions of species associations, it can be used to define or refine any established or new agroecosystem using objective criteria. For example, we showed that the services related to shade in agroforestry systems (e.g., regulation of microclimate and biomass production) depend on the zone of influence and the planting density of the tallest tree species. Therefore, the corresponding ESSU should be drawn around these species, accounting for their height, canopy size, etc. If different agroecosystems are similarly structured in space and time with the same TES, the corresponding ESSU of these different agroecosystems will be similarly shaped. For example, alley-cropping systems in the agroforestry case would be rectangular-shaped and include tree species and part of the cultivated inter-row (Fig. 5). The parallel can be extended to all types of row-organized agroecosystems: in the case of annual-based intercropping systems, the impact of the shade of the tallest herbaceous species will result in an ESSU similar to one for alley-cropping agroforestry (a

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rectangle including this species and the next cultivated row or strip—see Fig. 4). Generic forms of ESSU (of different sizes, though) can be defined for any given type of TES if the agroecosystems share similar diversity patterns. Such genericity should enable analytical comparisons between agroecosystems, standardize methods, and help design generic modeling modules that can be parameterized for each type of agroecosystem. Thus, the ESSU concept provides an efficient tool for agroforestry design and rapid monitoring and evaluation of TES over large and diverse landscapes.

We mentioned in the introduction that the ESSU concept is dedicated to various users (researchers, farmers, and agricultural advisers) dealing with the biological complexity of diversified agroecosystems, for different uses (design, model, audit). The richness of our concept comes from its ability to integrate the diversity of species and the TES they provide into a spatial unit. This spatial unit is concretely present in a crop model, but also in the field where it can even be delimited. The flexibility of our concept comes from the fact that its graphical representations are easily explicable, usable as tools of representation (Masure et al. 2022) and for dialog between actors. Thus, if it is obvious that researchers will represent diversified agroecosystems in models, they will be able to collect information and render it to farmers and agricultural advisers by mobilizing our concept and its graphic representations. The same is true among users of the concept for its other uses. Once known, the simplicity of use of our concept could also allow farmers themselves to represent their diversified agroecosystems or design prototypes to other actors.

5.3 Limits and perspectives

The ESSU formalizes the way species diversity is represented in space and time within agroecosystems by farmers to achieve TES provision objectives. Currently, as proposed here, it focuses on species taxonomy (e.g., species names and varieties) and status (e.g., crops, service plants, weeds, cattle, and pest controllers), the species development in time and space (e.g., size, stratum, age and animal population dynamic), and the species spacing design and density per unit of soil surface. This approach is highly relevant as it reflects how farmers and stakeholders generally deal with species diversity. However, ecological research increasingly reveals that plant functional traits rather than taxonomy strongly influence most ecological processes underlying ecosystem services. It also shows that farmers have a relevant perception of, and sometimes explicitly manage, trait diversity in agroecosystems (Garnier et al. 2016; Isaac et al. 2018). The ESSU concept could be developed further to provide a mechanistically sound approach for analytical, design, and modeling work by incorporating plant trait patterns into ESSU (e.g., the zone of influence of species), or even by building ESSU from trait distribution within agroecosystems. Additionally, the current ESSU concept hypothesizes that plant species associations are the primary drivers of TES. However, it recognizes that a range of other living, sometimes "hidden," organisms from different trophic levels may play an active if not pivotal role (e.g., soil fauna and micro-organisms for services related to biogeochemical cycles) (Deheuvels et al. 2014; Rousseau et al. 2012). More comprehensive knowledge of how the interaction network among all involved organisms is structured and evolves through time in agroecosystems would refine the 3D size, geometry, and dynamics of ESSU.

As proposed here, the ESSU does not account for the impacts of environmental heterogeneity (e.g., soil heterogeneity and slope) and adaptive management by farmers of species interactions and ecological processes underlying TES. Using ESSU to design the "best" association of species and habitats would define a potential TES rate, but the actual TES rate will be regulated by how farmers manage the ESSU in interaction with environmental conditions. Indeed, in heterogeneous environments, farmers may adapt their management strategy locally and express differently how a given ESSU will contribute to TES. On this basis, an agroecosystem could be conceptualized as several "in practice" versions of one ESSU, resulting from variations around a given set of species associations, environmental conditions, and management strategies. Defining "adjustable" farming practices relevant to TES would strengthen the ESSU concept. For all these reasons, the ESSU concept could contribute from a methodological point of view to the main challenge highlighted by Gaba et al. (2015) expressing an urgent need for the transition towards a more sustainable agriculture, clearly based on the functional links between species diversity, associated agricultural management, and the provided TES.

6 Conclusion and prospects

The ecosystem services functional spatial unit (ESSU) concept is a representation of in situ diversified agroecosystems and the targeted ecosystem services (TESs) they provide. We demonstrated that the ESSU concept is highly flexible and applicable to a wide range of diversified agroecosystems, with applications for arable intercropping, crop-tree intercropping, tree-tree agroforestry systems, and even agro-sylvo-pastoralism by including animals. When an ESSU is identified, it represents the smallest spatial unit to consider at a given time for the study of the TES provided by the species composition and

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arrangement, in a whole diversified agroecosystem. The ESSU concept is defined regarding a diversity of TES and not only the production service as is usually the case. It can be applied to evolving cropping systems, representing their different stages. A new stage starts when the TES change due to a modification in the technical management or in the species composition and arrangement.

The ESSU concept deals with crop diversification for agroecology, aiming to conceptually equip scientists working on intercropping and agroforestry systems. Agronomists have useful suites of scale concepts (plant, stand, plot/field and farm) and technical concepts (technical management sequence, cropping system, and farming system) that integrate technical management at different scales. Focusing on plant and animal taxonomy (e.g., species names and varieties), plant and animal status in the agroecosystem (e.g., crops, service plants, weeds, cattle, and pest controllers), and the species spacing design and density per soil surface unit, the proposed ESSU concept is both a complementary scale concept larger than the plant scale and a complementary technical concept describing the species interactions and the TES they provide. We propose a graphical representation of the ESSU (see figures in Sections 4 and 5) to operationalize the use of the concept.

In applying the ESSU concept to diversified agroecosystems, we demonstrated its relevance and suitability to represent temporal changes over 1 year (pruning of shade trees), across several years (changing inter-row management in a vineyard/orchard), and over decades (agroecosystem trajectory of diversification from an initial to a final cropping system), indicating its generalizability and flexibility. The user of the ESSU concept must decide the level of complexity required to build and adapt ESSU to meet their own objectives and TES. Because the ESSU concept allows both on/off and gradual representations of a TES provision area, we recommend integrating gradients of TES provision into ESSU when required (e.g., biological control of pests by insects or other animals).

The ESSU concept opens new research avenues for the study of diversified agroecosystems based on the ESSU concept. The ESSU concept also has a wide range of applications for researchers, farmers, and agricultural advisers dealing with the biological complexity of diversified agroecosystems. They can use it as a dialog and representation tool, like Masure et al. (2022). The ESSU is relevant for prioritizing views of analysis and for avoiding misunderstanding and misinterpretation of agroecosystem functioning. It can be used for (i) the (co) design of more efficient agroecological systems according to the TESs; (ii) rapid audit, evaluation, and monitoring of farming practices for diversity/resilience across large tracts of farmland as part of achieving SDG2 targets; and (iii) modeling such diversified agroecosystems using the smallest spatial unit adapted to represent the TES and the species spacing design. Finally, ESSU might be one component of the Duru et al.'s (2015) learning-support missing tools and knowledge gap about relations among practices, biodiversity, and associated ecosystem services. The ESSU concept could contribute to study and improve the performance of diversified agroecosystems in the transition to highly diversified agriculture.

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Authors' contributions SR: original idea, supervision, conceptualization, writing of definition and designing sections, of oil palm and Melanesian examples, of highlights of all sections, of conclusion, of abstract, review and editing, figures 1–3abcd–4ab–5abc–6–7–8–9–10, references section, tables 1–2, references section

MG: conceptualization, writing of modeling section, review and editing, figures 5bc–11

KB: conceptualization, writing of discussion section, review and editing

LG: conceptualization, writing of introduction section, vineyard example, review and editing, figure 2

CA: conceptualization, writing of coffee example, review and editing, figure 4ab

OD: conceptualization, rewriting of designing section, review and editing

JG: conceptualization, writing of initial modeling section, review and editing

PJ: conceptualization, writing of cocoa example

PEL: conceptualization, section 4 review, writing of orchards example, review and editing, figure 5a

AnM: conceptualization, writing of paragraphs in discussion section, review and editing

AuM: conceptualization, writing of metrics section, vineyard example, review and editing, figure 2

FR: conceptualization, writing of initial modeling section, review and editing

SS: conceptualization, writing of cocoa example, review and editing, figure 9

GNC: review and editing of last versions of the paper, writing of paragraphs

EJ: supervision, conceptualization, writing of single stratum intercropping examples, review and editing, figure 3abcd

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Consent of all authors.

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