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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 '-') Agroecology - Ecosystem services - Intercropping - Agroforestry - SDG 2

Footnote Information



2 The ESSU concept for designing, modeling, and auditing ecosystem 3 service provision in intercropping and agroforestry systems. A review

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9 Abstract

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12 for designing, modeling, monitoring, and auditing desired ecosystem services, in intercropping and agroforestry systems.
13 This concept delimits the smallest spatial unit called ESSU, encompassing all the interacting species and other func-
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28 practices, biodiversity, and associated ecosystem services.

29 **Keywords** Agroecology · Ecosystem services · Intercropping · Agroforestry · SDG 2

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30 **Contents**

31 1. [Introduction](#)

32 2. [The concept of Ecosystem Services functional Spatial Unit](#)

33 2.1. [Description](#)

34 2.2. [How to identify and represent an ESSU?](#)

35 3. [Application of the ESSU concept to describe a wide](#)

36 [range of intercropping and agroforestry systems](#)

37 3.1. [Single stratum intercropping systems](#)

38 3.2. [Multi-strata agroforestry systems](#)

39 4. [Use of the ESSU concept](#)

40 4.1. [Auditing ecosystem services provision in diversi-](#)

41 [fied agroecosystems](#)

42 4.2. [Modeling diversified agroecosystems using the](#)

43 [ESSU concept](#)

44 4.3. [Designing diversified agroecosystems](#)

45 5. [Novelty, genericity and limits of ESSU concept](#)

46 5.1. [Novelty of the ESSU concept](#)

47 5.2. [Generalizability of the ESSU concept](#)

48 5.3. [Limits and perspectives](#)

49 6. [Conclusion and prospects](#)

50 7. [Acknowledgements](#)

51 8. [Declarations](#)

52 9. [References](#)

53 **1 Introduction**

54 This review deals with the discipline of agroecology that
 55 seeks to enhance ecological processes to support the pro-
 56 duction of agricultural goods and ecosystem services (e.g.,
 57 Wezel et al. 2009; 2014). Agroecology is increasingly being
 58 accepted as a discipline to simultaneously: (i) produce food,
 59 forage, bio-energy, and bio-components; (ii) protect the
 60 environment (soil, air, water), ecosystem diversity, and the
 61 planet against climate change; and (iii) safeguard human
 62 health, particularly by reducing pesticide use (e.g., Vander-
 63 meer 1995; Deguine et al. 2017; FAO 2018). Agroecology
 64 may also favor both the adaptation to and mitigation of cli-
 65 mate change by enhancing the resilience of agroecosystems
 66 (Wezel and David 2012; Saj et al. 2017) and sequestering
 67 carbon in soils and trees (e.g., Altieri and Nicholls 2017).
 68 Duru et al. (2015) framed agroecology as a “diversity-
 69 based agriculture” where a high level of biological diversity
 70 replaces chemicals and other external inputs by providing
 71 ecosystem services.

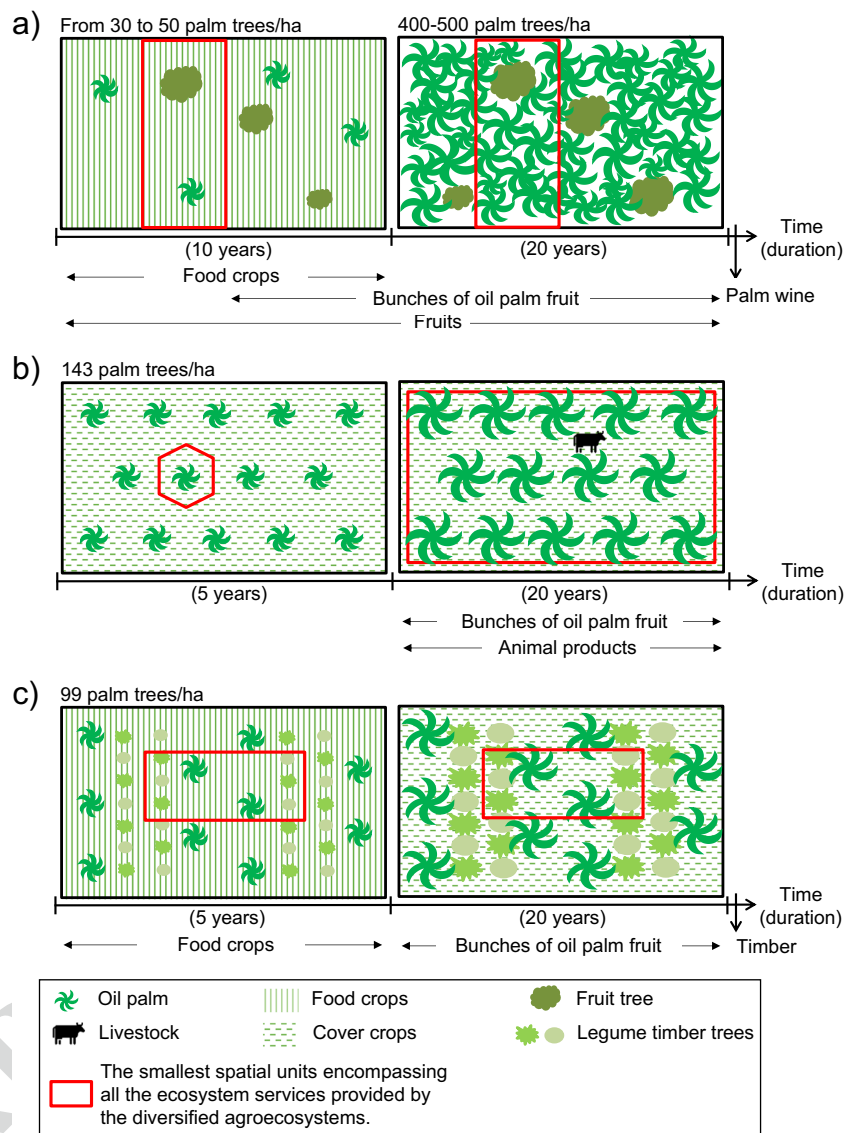
72 Diversified agroecosystems can be conceived in two
 73 dimensions: (i) in time, with crop succession of various spe-
 74 cies in cropping systems based on arable and forage crops;
 75 and (ii) in space, where species are grown together in the
 76 same space, such as through intercropping and agroforestry
 77 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 pos-
 sibly 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 Rich-
 ard 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 rota-
 tion) 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 ecosys-
 tem services (Garcia et al. 2018; Nijmeijer et al. 2019). Like-
 wise, field management techniques and spatio-temporal pat-
 terns 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 eco-
 system functions. Ecological “processes” define how liv-
 ing 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
 et al. 2011; Duru et al. 2013). Ecosystem services give rise

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).



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

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

- 142 • provisioning services, that is, *nutritional, non-nutritional*
 143 *materials, energetic, and abiotic outputs from ecosystems*;
- 144 • regulation and maintenance services, that is, *mediation or*
 145 *moderation of the ambient environment by living organ-*
 146

isms or non-living processes that affect human well-being; and 147

- cultural services, that is, *non-material biotic or abiotic*
 149 *outputs of ecosystems that affect physical and mental*
 150 *states of people.* 151

152 We define a targeted ecosystem service (TES) as an eco-
 153 system service that farmers and stakeholders value. It shapes
 154 their choices regarding diversity when managing, designing,
 155 or optimizing a diversified agroecosystem. Depending on
 156 the complexity of the agroecosystem, the number of TESs
 157 can vary considerably and may change through time, follow-
 158 ing the production cycles and the composition of the plant
 159 communities, especially for perennial crops and trees. Gaba
 160 et al. (2015) consider that the main challenge for the transi-
 161 tion towards a more sustainable agriculture is to design new
 162 cropping systems where the plant diversity and associated

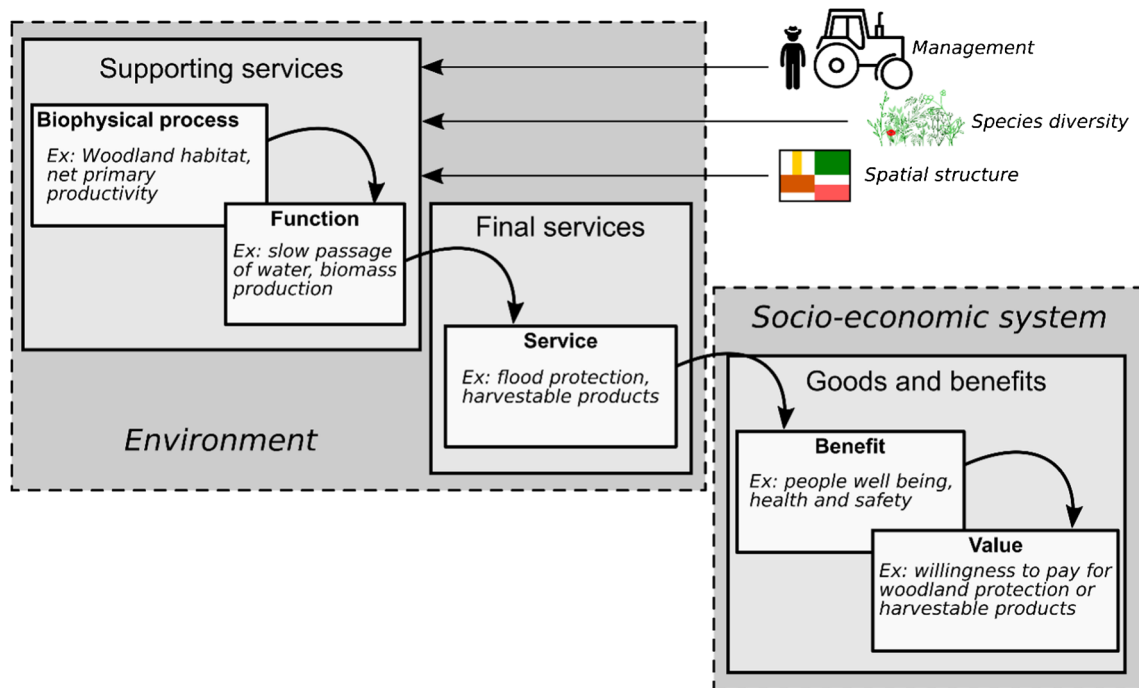


Fig. 2 The present work builds on the ecosystem service cascade framework where ecosystem services are defined as “contributions that ecosystems [including agroecosystems or managed ecosys-

tems] make to human well-being” (adapted from Haines-Young and Potschin 2010; 2016; 2018).

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

165 Ecological functions have a pivotal role between ecosys-
 166 tems and human activities as they reflect the aggregated,
 167 visible, and manageable subset of subtending ecological
 168 processes (de Groot et al. 2002; Haines-Young and Potschin
 169 2016). Ecological functions can be evaluated using biophys-
 170 ical proxies to study the ecological (e.g., effects of diversity)
 171 and agronomic (e.g., effects of management) determinants of
 172 ecosystem services in varying contexts (Lavorel et al. 2013).
 173 In agroecosystems, the ecological functions and services
 174 usually rely on a limited number of spontaneous or man-
 175 aged species (e.g., sown or planted vegetation or introduced
 176 animals) and may be enhanced by management (e.g., con-
 177 servation, or biological control). Each function relies on a
 178 specific combination of (i) plant and/or animal diversity; (ii)
 179 functional properties of this diversity; (iii) its arrangement
 180 in space and time; and (iv) farmers’ management strategies.
 181 Some services are provided continuously along one crop
 182 cycle (e.g., soil organic matter improvement), while other
 183 services are provided at points in time or over given time
 184 scales according to abiotic and biotic conditions. Conse-
 185 quently, it is essential that agroecosystem management takes
 186 into account the dynamics of the provision of ecosystems
 187 services (Schipanski et al. 2014; Garcia et al. 2018).

188 However, Duru’s et al. (2015) review article suggests “a
 189 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.” Search-
 ing 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 prac-
 tical 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 (Rafflegeau 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 veg-
 etation, semi-natural habitats such as hedges, ditches, and
 forest patches) that together provide a specified set of eco-
 system services represented in a farming landscape. We have

215 labeled this smallest spatial unit the “Ecosystem Services
216 functional Spatial Unit” (ESSU) to highlight its spatially
217 recurring combination of characteristics within a farming
218 landscape. Its repetition in space allows representation of
219 an entire diversified agroecosystem. The main value of the
220 ESSU concept lies in its capacity to represent simply the
221 targeted ecosystem services of diversified agroecosystems.

222 The ESSU concept can be utilized by researchers, farmers,
223 and agricultural advisers dealing with the biological complex-
224 ity of diversified agroecosystems and seeking to design,
225 model, and audit farming systems to maximize desired
226 ecosystem services. Because of its capacity for use across
227 a broad range of cropping systems and scales (plot, farm,
228 and territory) within farming landscapes, it has potential
229 applications in monitoring and evaluation in the efforts to
230 address Sustainable Goal 2: Zero Hunger, particularly Target
231 2.4 (United Nations Sustainable development Goals 2022):

232 By 2030, ensure sustainable food production systems
233 and implement resilient agricultural practices that
234 increase productivity and production, that help main-
235 tain ecosystems, that strengthen capacity for adap-
236 tation to climate change, extreme weather, drought,
237 flooding and other disasters and that progressively
238 improve land and soil quality.

239 We first propose such a concept because there is no agro-
240 nomical concept corresponding to the computer science con-
241 cept of a simplified scene of the system when modeling a
242 diversified agroecosystem. Secondly, agronomists do not use
243 a concept to represent a whole system integrating cultivated
244 species, spacing design, technical management, the TES, and
245 their provision areas, which are necessary for designing diver-
246 sified agroecosystems. Thirdly, we need to represent and com-
247 pare agroecosystems when auditing the TES they provide, and
248 ESSU could be the simplified representation of the system.

249 Technical support is still mainly based on agrochemicals
250 and the labor force rather than on services provided by intro-
251 ducing biodiversity in agroecosystems. In addition, advances
252 in agricultural and ecological sciences are necessary to bet-
253 ter predict the effects on biodiversity in agroecosystems in
254 response to planned modifications of agroecological prac-
255 tices from field to landscape level (Duru et al. 2015). The
256 importance of developing such knowledge, tools, and capac-
257 ity is heightened with the urgency of the UN’s 2030 SDG
258 Target 2.4 to “ensure sustainable food production systems
259 and implement resilient agricultural practices.”

260 The “Ecosystem Services functional Spatial Unit”
261 (ESSU) proposed here is designed to accommodate the bio-
262 logical and structural complexity of diversified agroecosys-
263 tems. The ESSU concept aims to broaden the conceptual
264 tools of agronomy to facilitate uptake of agroecological
265 approaches for dealing with a continuum of diversification in
266 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 applica-
tions 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 evalu-
ation 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 agro-
ecosystems 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, ser-
vice 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 larg-
est 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 com-
plementary 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.

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 above-ground flora/fauna, and their dynamic interactions over time. Depending on species architectures (above and below-ground) 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

414 (Fig. 3a) or in alternate rows (Fig. 3b). In both cases, the
 415 same ecosystem services are commonly targeted (TES 1 and
 416 TES 2). As the interspecific interactions occur at the indi-
 417 vidual plant level or at the level of a few plants organized
 418 in a homogenous group, the whole plot can be considered
 419 as the repetition of one ESSU comprising a few rows. In
 420 the situation of mixed species within the row (Fig. 3a), it
 421 is convenient to set the ESSU as 1 m² of mixed species to
 422 avoid micro-spatial heterogeneity due to mechanical sowing,
 423 even if it could also be determined theoretically according
 424 to the plant density (e.g., one legume plant and four cereal
 425 plants). In the alternate rows situation (Fig. 3b), the ESSU
 426 can be set as 1 row of each species of 1 m length (also to
 427 avoid micro-spatial heterogeneity of inter-plant distance due
 428 to mechanical sowing).

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

437 The alternate strips of crop and uncultivated grass
 438 (Fig. 3d) could be effective for reducing run-off, soil erosion,

439 and surface water pollution on slopes. Indeed, grass strips
 440 are effective for reducing soil and pollutants transfer and
 441 for enhancing diversity in soils and vegetation by providing
 442 animal habitats. These TES can be summarized in two types:
 443 production (TES 6) and regulation (TES 7). The provision
 444 area of these TES is spatially dependent and consequently
 445 defines the limits of the ESSU.

3.2 Multi-strata agroforestry systems

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

3.2.1 Coffee-based agroforestry systems

451 In simple coffee-based agroforestry systems, coffee trees are
 452 associated with a single species of service tree. For exam-
 453 ple, in Costa-Rica, the most popular associated species in
 454 coffee plantations is the leguminous *Erythrina poeppigi-*
 455 *ana* (Meylan et al. 2017). The ecological functions associ-
 456 ated with *E. poeppigiana* are mainly related to soil nutrient
 457 availability by increasing total and inorganic N content, N
 458

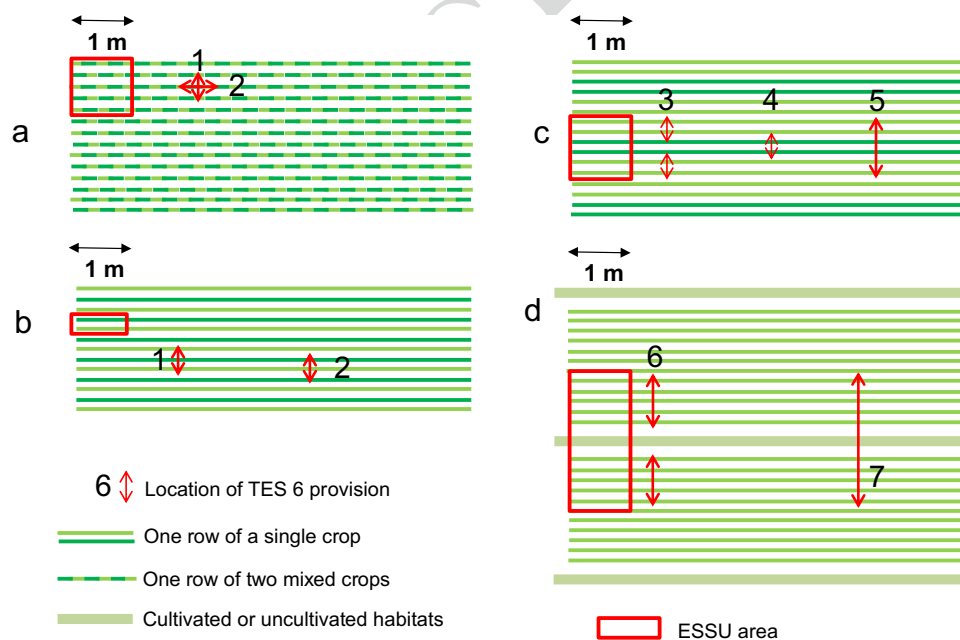


Fig. 3 Application of the ecosystem services functional spatial unit (ESSU) concept to four types of intercropping systems based on arable crops: (a) mixed crops in the same row; (b) mixed crops on alternate rows; (c) mixed crops on alternate alleys; (d) single crop in alley, alternating with uncropped 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 N₂ 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.

459 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).

474 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.

481 *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,

486 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

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

496 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; Demestihias 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

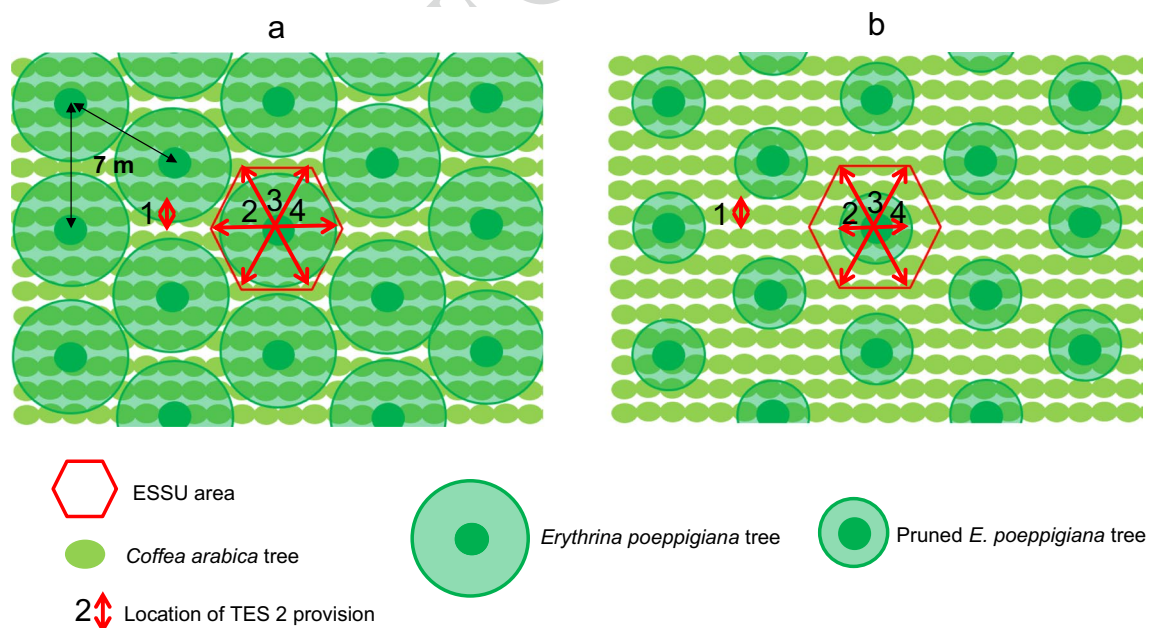


Fig. 4 Mature arabica agroforestry systems managed by smallholders in Costa-Rica: the targeted ecosystem services (TES) described in the text are all within the hexagonal ecosystem services functional spatial unit (ESSU). Heavy pruning at coffee flowering does not alter the ESSU. The red hexagon delimits 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.

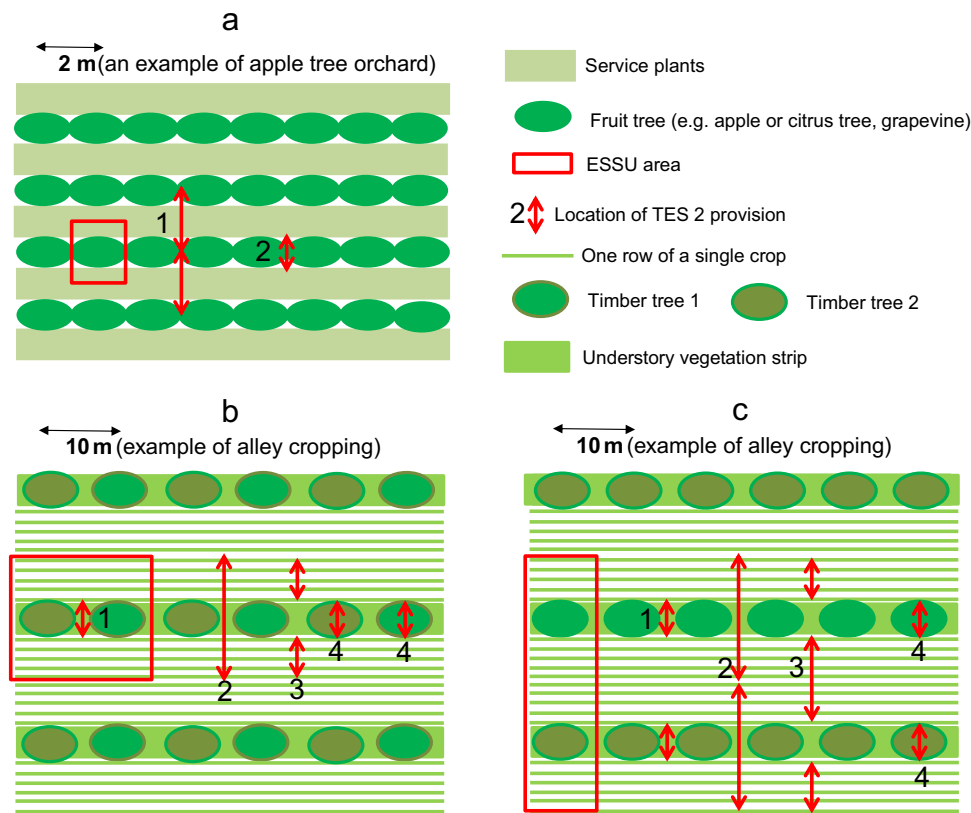


Fig. 5 **a** Application of the ecosystem services functional spatial unit (ESSU) concept in two-strata orchards where fruit trees (e.g., apple trees, citrus or grapevines) are in rows and service plants in interrows. The distance between trees in rows varies depending on the tree species and on the 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, pollina-

tion 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.

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

516 Figure 5b and c presents examples of agroforestry systems
 517 based on alley-cropping (e.g., timber tree rows with
 518 spacing allowing mechanized production of the crops in
 519 the alleys between tree rows). Three types of vegetation
 520 strata can be identified, each one providing a TES: the high
 521 strata trees (main TES, wood production); the crop, possi-
 522 bly including medium strata trees (main TES, food or
 523 feed production); and the understory vegetation strip (main
 524 TES, refuge for plant diversity, natural habitats for benefi-
 525 cial arthropods, carbon storage; see Boinot et al. (2019)).
 526 Thus, the ESSU encompasses all three or more strata in
 527 their respective densities, and contains the whole gradient of
 528 interactions between the three elements. Due to the potential
 529 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 spe-
 cies 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 diver-
 sity of food crop species (short-cycle crops like maize and

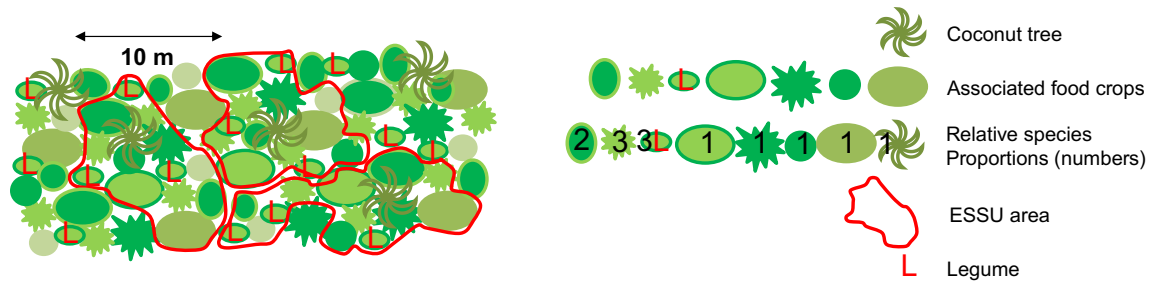


Fig. 6 The ecosystem services functional spatial unit (ESSU) concept also applies to highly diversified multi-strata agroforestry systems associating irregularly spaced short and long-cycle food crops,

such as traditional Melanesian food gardens. The red lines demarcate ESSU boundaries. All targeted ecosystem services: food crop production and complementary access to resources.

547 peanuts and longer-cycle crops like tubers, scattered plan-
 548 tains and pawpaw trees, and often bordered with coconut
 549 palms), irregular spacing, no fallow period, no fertilizer,
 550 plant scale rotation of species, and fertile volcanic soils (Ver-
 551 gara and Nair 1985; Clarke and Thaman 1993). Commonly,
 552 TES may be production and complementary uses of space
 553 and resources during the different phases of the cropping
 554 cycles. By focusing on a qualitative approach to ecosystem
 555 services provision when designing the ESSU, an exhaus-
 556 tive description of all different component species and their
 557 spatial arrangement is not necessary. Instead, species can be
 558 grouped according to the functions they perform, in order to
 559 simplify the representation of the spatial arrangements. Due
 560 to the irregular spacing of the different cultivated species in
 561 the field, the boundaries of the corresponding ESSU have
 562 an irregular shape (Fig. 6).

563 **3.2.4 Highlights of Section 4**

564 We highlight the transversal rules to define the ESSU
 565 in different agroecosystems. ESSU boundaries depend
 566 mainly on the species that provides the TES with the larg-
 567 est provision area. Regular spacing leads to a polygonal
 568 shape of ESSU; square or rectangular spacing leads to an
 569 ESSU with square or rectangular shape (Fig. 3a, 3b, 3c,
 570 3d, 5a, 5b, 5c); and triangular spacing of shading trees
 571 (Fig. 4) leads to an hexagonal ESSU shape (Table 1). In
 572 contrast, irregular spacing leads to an irregularly shaped
 573 ESSU (Fig. 6).

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

4 Use of the ESSU concept

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

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4.1 Auditing ecosystem services provision in diversified agroecosystems

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

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Complex systems raise the question of how they can be char-
 acterized, 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 vari-
 ables 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).

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Metrics can be established for the different components
 of the ESSU such as crops, soils, weeds, and pests. To spec-
 ify 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 deter-
 mining the TES and can be mobilized for the monitoring

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

Type of spacing design	Shape of spacing design	ESSU boundary shape design
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

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

614 The ESSU concept can provide a rapid and standardized
615 tool for auditing ecosystem service provision across agro-
616 forestry systems, and can also indirectly help the develop-
617 ment of analytical tools, representations, and indicators use-
618 ful for auditing. The concept facilitates easy comparisons
619 of the provided TES across different agroforestry systems
620 and enables determination of the diversity and frequency
621 of the TES provided, all important for auditing ecosystem
622 services provision. This capacity to audit ecosystem services
623 provision and monitor their change in response to develop-
624 ment interventions is becoming increasingly important in
625 the context of the UN's Sustainable Development Goal 2,
626 **AK3** Target 2.4 (see Section 2). ESSU is a tool for establishing
627 baselines in ecosystem service provision and for assessing
628 progress towards Target 2.4 in terms of improved resilience
629 of agricultural systems and strengthened adaptive capacity.

630 **4.2 The ESSU concept: a tool to assess the spatial** 631 **gradient of TES provision**

632 The intensity of TES provision was spatially homogeneous
633 in all the cases presented in Section 4. Nonetheless, many
634 ecological "processes" show spatial variability by species
635 and agroecological infrastructure (e.g., shade intensity varies
636 spatially with canopy density and shelter varies with dis-
637 tance from tree hedges). We describe in this section how the
638 ESSU concept could represent a spatial gradient of biologi-
639 cal control of pests at the landscape scale.

640 Figure 7 is a hypothetical area of farmland that includes
641 strips of uncultivated habitats and a complex field margin
642 that generates edge effects. This field margin is L-shaped and
643 separates three fields: one vineyard and two fields of mixed
644 annual crops. In such landscapes, the ESSU concept can
645 illustrate how the farmer manages biological control of pests
646 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 (García 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 appropriate 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

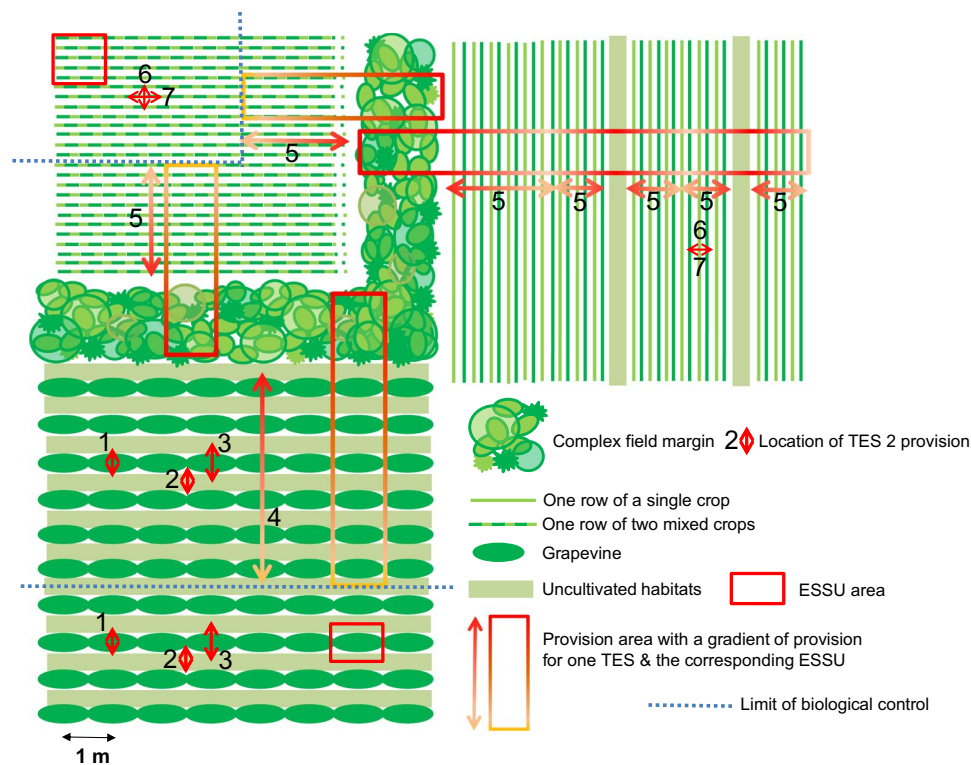


Fig. 7 In this hypothetical area of farmland, the different ecosystem services functional spatial units (ESSU) show the effects of the agroecological infrastructures (a complex field margin and strips of uncultivated habitats) on biological control of pests by insects and other animals, at the field 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.

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

692 Similarly, in the field of annual crops mixed in the row,
 693 the provision area for the TES of biological control of
 694 pests (Fig. 7; TES 5) is limited to a specified distance from
 695 the complex field margin (e.g., Boinot et al. 2019; Cordeau
 696 et al. 2012). Its extent determines the shape of the ESSU
 697 for this part of the field, including the TES provision area
 698 for annual crops production (Fig. 7; TES 6) and niche
 699 complementarity for nitrogen resources (Fig. 7; TES 7).
 700 In the field of annual crops sown in strip intercropping,
 701 both the complex field margin and the strips of unculti-
 702 vated habitats provide complementary and independent
 703 gradients of biological control of pests. The uncultivated
 704 strips are optimally located in relation to the field margin
 705 and from each other to provide some level of biological
 706 control of pests everywhere in the field (Fig. 7 TES 5). In
 707 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.

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

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

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

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

751 This example illustrates how the ESSU concept can
 752 (i) represent the evolution through time of diversified

cropping systems; and (ii) audit the ecosystem services 753
 provided during evolutionary paths of agroecosystems. 754

4.2.2 The ESSU concept: a tool for comparing different 755
 pathways in transitioning agroecosystems 756

Farmers choose different pathways and strategies when tran- 757
 sitioning from one agroecosystem to another. This is the case 758
 in Central Cameroon, where the perennial grass, *Imperata 759*
cylindrica, is a major barrier to the establishment of cocoa 760
 on savannah land. Farmers have developed two success- 761
 ful strategies to eliminate this grass (Jagoret et al 2012). 762
 The first strategy, which is more labor efficient but has less 763
 potential for food gardening during the transition phase, 764
 consists of hand-sowing oil palm at high density (ca. 1200 765
 individuals ha⁻¹) to create a dense shade that eliminates 766
I. cylindrica within four to 5 years. Then, farmers reduce 767
 the density of palms (to less than 100/ha⁻¹), and use felled 768
 palms to produce palm wine. They also introduce cocoa and 769
 fruit trees and retain some self-seeded forest trees as shade 770
 for the developing cocoa. The second strategy, which is more 771
 labor-intensive but provides more land for food gardening 772
 in the transition phase, utilizes annual food crops. Farmers 773
 carry out a deep manual ploughing and then successively 774
 sow some short-cycle species (peanuts, cucumbers, maize, 775
 etc.). Ploughed rhizomes of *I. cylindrica* are exposed to sun- 776
 light and rapidly dry out. After two or 3 years of cultivation, 777

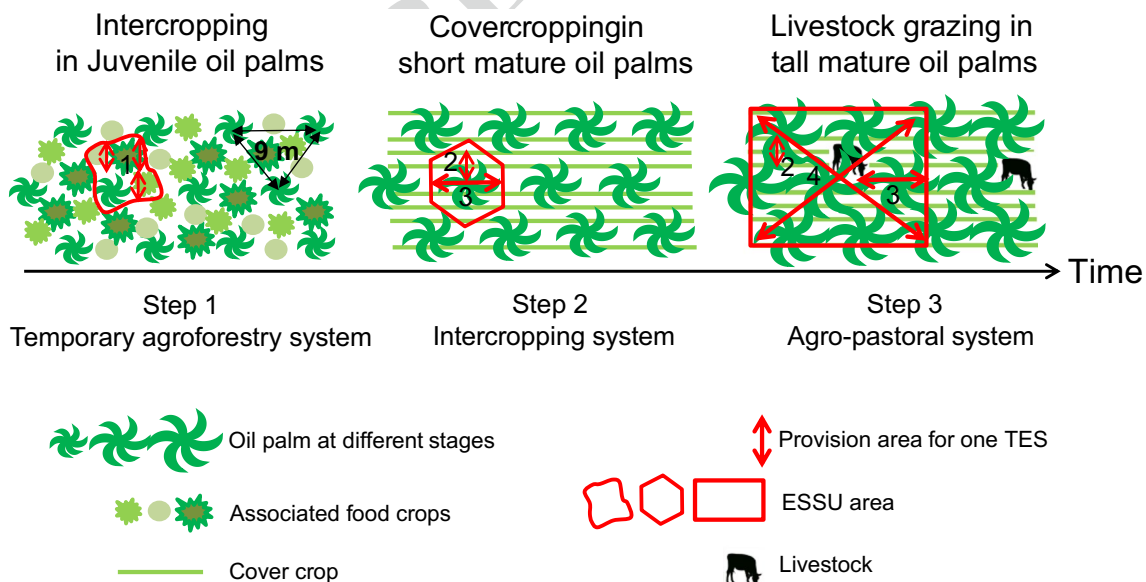


Fig. 8 Analysis of the evolution of a diversified oil palm cropping system in Cameroon over three decades. The services functional spatial unit (ESSU) evolves in three steps from juvenile palms (step 1) to short stature mature palms (step 2) and then to diversification with animals (step 3). The red lines delimit ESSU; num-

bers 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.

778 farmers introduce cocoa and fruit trees while retaining some
 779 self-seeded forest trees.
 780 Under both strategies, the cocoa agroforestry systems
 781 initially established on savannah mature and become like
 782 agroforestry systems initially established on partially cleared
 783 forest (Fig. 9). While aging, these cocoa agroforestry systems
 784 lose some of their associated perennials either due to
 785 shade control or to senescence. For both transition strategies,
 786 the cocoa trees are managed in a similar way to cocoa systems
 787 that are initially established on partially cleared forest
 788 (Jagoret et al. 2018). Thirty to 70 years after establishment,
 789 they also reach similar provision levels of most TES (Nijmeijer
 790 et al. 2019). These two strategies underline the different
 791 phases through which these long-lived agroforestry systems
 792 can develop. In the first strategy, the very dense oil palm
 793 stand provides the TES of elimination of *I. cylindrica*, and
 794 later, the TES of palm wine production; while in the second
 795 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

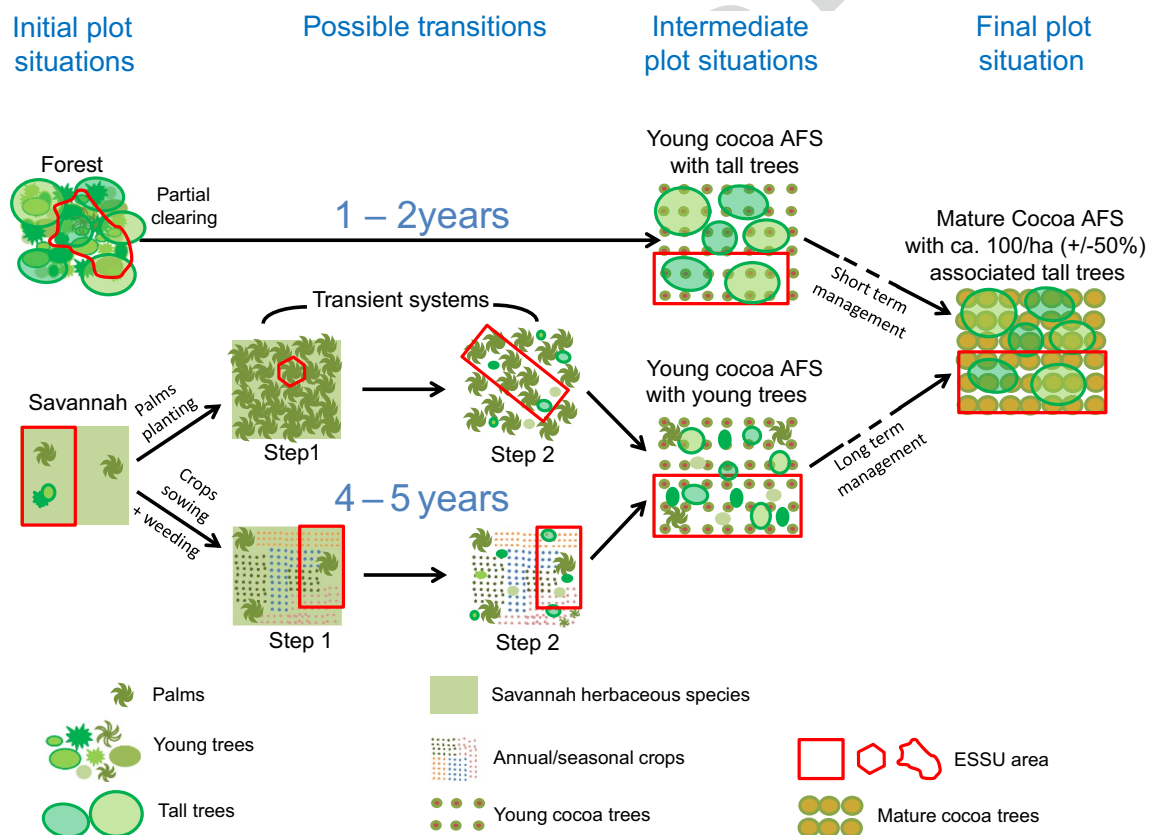


Fig. 9 Possible transition trajectories from forest or savannah to a mature cocoa-based agroforestry system (AFS). In forest, farmers hunt and gather irregularly spaced forest products; thus, the ecosystem services functional spatial unit (ESSU) has an irregular shape. In savannah, farmers produce annual 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 overshadowing. 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.

811 yields and other plant/environmental variables for crop-
812 pping, intercropping, and agroforestry systems, under the
813 influence of various environmental conditions and techni-
814 cal management practices (e.g., fertilization, irrigation, and
815 tree pruning).

816 Models should be as simple as possible, yet provide a
817 meaningful representation of reality. However, the spatial
818 distribution of different species is of major importance for
819 species interaction and environmental services in diversif-
820 ied agroecosystems (Anderson and Sinclair 1993; Jose
821 et al. 2004). In this context, the ESSU concept is useful as
822 it helps identify the smallest spatial area characterizing the
823 heterogeneous distribution of plants and their interactions
824 in diverse agroecosystems (Gaudio et al. 2019). In spatially
825 explicit models, edge effects are usually accommodated by
826 defining boundary conditions, that is, deciding what happens
827 when something (a particle, or, in the case of crop models,
828 a plant organ, pest propagule, or tree shadow) reaches the
829 edge of the simulated spatial domain. There are three types
830 of boundary conditions: (i) periodic (what goes across the
831 right border comes back across the left border); (ii) refle-
832 ctive (everything “bounces back” when reaching the border);
833 and (iii) absorbing (things disappear when they go outside
834 the simulated area). Periodic boundary conditions simulate
835 infinite space, as if the patterns in the simulated area were
836 repeated in all directions like a tiled surface. The ESSU,
837 being an individual tile in a tiled space, should be mode-
838 led using periodic boundary conditions. For square (e.g.,
839 Fig. 3a), rectangular (e.g., Fig 5a), or hexagonal (e.g., Fig
840 4) ESSU, defining periodic boundaries is straightforward.
841 For an irregularly shaped ESSU (e.g., Fig. 6), the modelers
842 have to reshape the ESSU into a regular shape, keeping not
843 only the composition (i.e., the proportion of each species),
844 but also, as much as possible, the configuration (both in

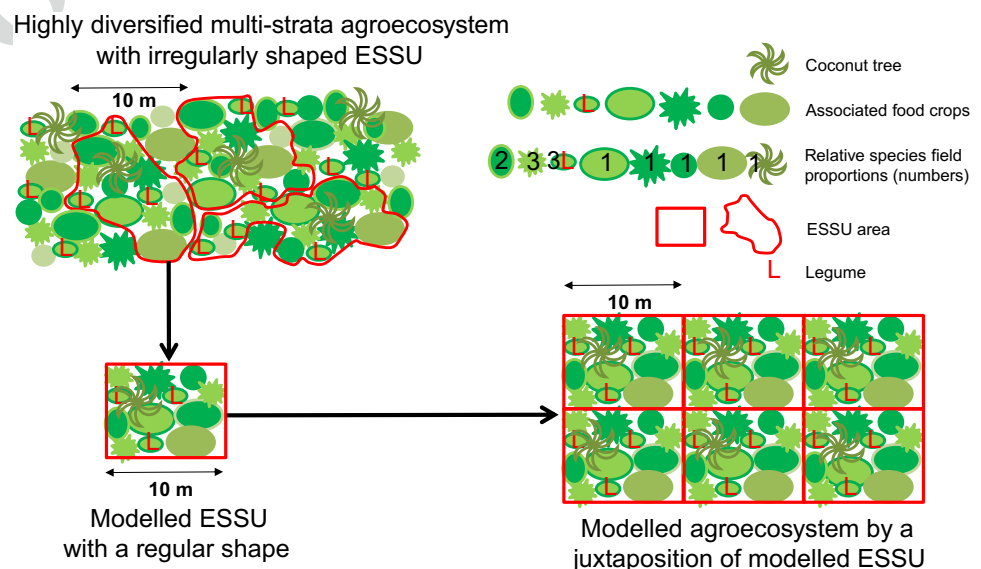
845 topological terms, that is, the connections between neigh-
846 boring species and in terms of distances between species). This
847 allows the whole space to be represented as a juxtaposition
848 of the modeled ESSU (Fig. 10).

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

857 4.3.2 Examples of model spatial domain definition using 858 the ESSU concept

859 Hi-sAFe is a 3D agroforestry model for representing tree-
860 crop interactions and their effects on some ecosystem ser-
861 vices and dis-services. These include tree and crop produc-
862 tion (taking into account tree-crop competition for light,
863 water, and nitrogen) and regulation of groundwater quality
864 (of the water cycle, of crop temperature, etc.) (Dupraz et al.
865 2019). To represent the simulated area (called the “scene”),
866 the model can use absorbing and/or periodic boundary con-
867 ditions on the different borders: an infinite agroforestry sys-
868 tem (periodic boundary conditions on all sides); a forest or
869 agroforestry field edge (one side with absorbing conditions);
870 or a hedgerow (two opposite sides with absorbing condi-
871 tions). Although the scene can theoretically be of any size
872 and contain any number of trees, the smaller it is, the shorter
873 the computation time. For the representation to be practi-
874 cal, the scene should thus not exceed the areal extent of the
875 ESSU. In the simplest case—an alley cropping agroforestry
876 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).



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

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

909 The STICS soil-crop 1D model was initially developed
 910 for single crops (Brisson et al. 2008) and it was adapted
 911 to intercropping for simulating bi-specific alternate row
 912 intercropping systems organized in a simple spatial pattern
 913 (Brisson et al. 2004; Vezy et al. 2022). Here again, the mod-
 914 elers used the ESSU concept without naming it specifically.
 915 Indeed, they considered that the most important interaction
 916 between species was light competition (driving the services

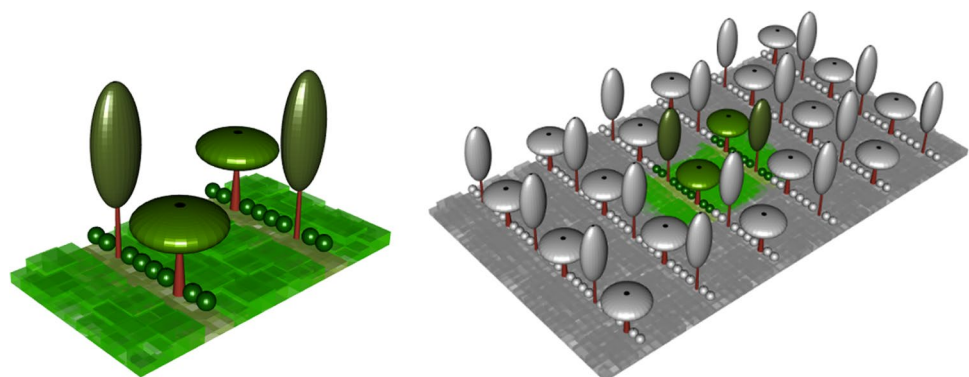
of crop production and temperature regulation), and defined
 the scene as the ESSU for these TES. The ESSU corre-
 sponds to the two species represented by half the canopy
 of one species, a half-canopy of the other species, and the
 inter-row distance between them. Other spatial aspects were
 neglected (e.g., spatial niche complementarity between root-
 ing 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 design-
 ing intercropping systems, agronomists are used to consid-
 ering 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 agroecosys-
 tems 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 crop-
 ping 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 prac-
 tices 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).

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

1055 and environmental benefits provided by agroforestry—Jose
1056 2009).

1057 The ESSU concept sits at the interface between the
1058 knowledge on TES in diversified agroecosystems and the
1059 available frameworks (e.g., ecosystem service cascade
1060 framework presented in Fig. 2; Alam et al. (2014) frame-
1061 work), while being useful for existing intercrop and agrofor-
1062 estry models (Section 5.3.2). Daryanto et al. (2020) identi-
1063 fied significant knowledge gaps regarding multiple aspects
1064 of intercropping, including examination of the effects of
1065 different crop combinations on ecosystem services. Our
1066 concept enables the ecosystem effects of different crop com-
1067 binations to be explored. Furthermore, in a review article
1068 about European agroforestry, Fagerholm et al. (2016) high-
1069 light that research on the linkages between agroforestry and
1070 ecosystem services have not been fully explored, suggesting
1071 a need for stronger consideration of stakeholder participa-
1072 tion to define, map, value, and foster ecosystem services.
1073 Because our concept builds graphic representations of the
1074 TES provided (Masure et al. 2022), it could offer an effective
1075 method, based on well-identified methodological steps,
1076 for assisting stakeholders through visualizing the provision
1077 area of the TES. Similarly, Juventia et al. (2022) propose
1078 a novel framework using graphic representation to include
1079 spatio-temporal aspects of strip cropping system design.
1080 This framework dedicated to strip cropping systems repre-
1081 sents the rotations at the strip scale in the cropping system.
1082 It complements the more generic ESSU concept represent-
1083 ing the TES and the species arrangements at ESSU scale,
1084 in all diversified agroecosystems. Both are conceptual tools
1085 addressing the call by Duru et al. (2015) for learning-support
1086 tools for the generation of knowledge about relations among
1087 practices, biodiversity, and associated ecosystem services for
1088 adaptive management.

1089 **5.1 Novelty of the ESSU concept**

1090 Agroecology thinking constitutes a significant break from
1091 “traditional” post-green revolution agronomy concepts in
1092 several aspects. Diversified agroecosystems are more com-
1093 plex and have more TES than existing widespread single-
1094 crop systems, based essentially on the single TES of crop
1095 production. Indeed, introduced biodiversity “complexifies”
1096 agroecosystem analysis, management, and assessment (Duru
1097 et al. 2015; Merot and Wery 2017). This is because the
1098 inputs oriented to each biophysical compartment are con-
1099 sidered separately and each species is considered indepen-
1100 dently from others in terms of ecosystem service provision
1101 and spatial organization. Because of this complexity, the
1102 management unit cannot be defined at the field plot level as
1103 done in the “cropping system” framework. In this respect,
1104 the ESSU brings a robust strategy to recognize that multi-
1105 ple functions are managed simultaneously for multiple

1106 TES, and that diversity patterns within a field plot determine
1107 them. They define a new scale of analysis and management
1108 between the levels of plant and plot. By doing so, ESSU also
1109 highlights the idea that spatio-temporal patterns of organ-
1110 isms are essential components of diversity in the functioning
1111 of agroecosystems. Thus, the ESSU concept offers an effective
1112 method for accommodating complexity.

1113 The areal extent of ESSU is not necessarily limited to the
1114 scale of cropping systems because ESSU can be defined at
1115 the “landscape” scale (*sensu lato*). This can include several
1116 cropping systems and elements that have been historically
1117 excluded from the management scope of agronomy like
1118 field margins, hedgerows, and surrounding natural habitats.
1119 In addition, ESSU can extend beyond short-term crop suc-
1120 ceSSIONS and deal explicitly with long-term trajectories of
1121 change of agroecosystems. The proposed ESSU concept
1122 extends the boundaries of agronomic concepts and scales
1123 (e.g., plant, plot, farm) and proposes a modular frame-
1124 work able to accommodate diverse spatial and temporal
1125 scales which is not easy with input-based approaches. As
1126 anticipated by Duru et al. (2015), the ESSU concept could
1127 increase attention on ecological functions and raise new
1128 research questions, not only for agronomy or agroecology,
1129 but also in soil and water sciences, animal ecology, land-
1130 scape ecology, and human geography.

1131 **5.2 Generalizability of the ESSU concept**

1132 The ESSU concept can be applied across a broad range
1133 of agroecosystem types. We demonstrated its usefulness
1134 for comparative analyses, modeling work, and presented
1135 a four-step methodology for formalizing the design of
1136 complex agroecosystems such as intercropping and agro-
1137 forestry. Because ESSU represents the link between the
1138 structure and the functions of species associations, it can
1139 be used to define or refine any established or new agroeco-
1140 system using objective criteria. For example, we showed
1141 that the services related to shade in agroforestry systems
1142 (e.g., regulation of microclimate and biomass production)
1143 depend on the zone of influence and the planting density
1144 of the tallest tree species. Therefore, the corresponding
1145 ESSU should be drawn around these species, accounting
1146 for their height, canopy size, etc. If different agroecosys-
1147 tems are similarly structured in space and time with the
1148 same TES, the corresponding ESSU of these different
1149 agroecosystems will be similarly shaped. For example,
1150 alley-cropping systems in the agroforestry case would be
1151 rectangular-shaped and include tree species and part of the
1152 cultivated inter-row (Fig. 5). The parallel can be extended
1153 to all types of row-organized agroecosystems: in the case
1154 of annual-based intercropping systems, the impact of the
1155 shade of the tallest herbaceous species will result in an
1156 ESSU similar to one for alley-cropping agroforestry (a

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

1258 arrangement, in a whole diversified agroecosystem. The
 1259 ESSU concept is defined regarding a diversity of TES and
 1260 not only the production service as is usually the case. It
 1261 can be applied to evolving cropping systems, representing
 1262 their different stages. A new stage starts when the TES
 1263 change due to a modification in the technical management
 1264 or in the species composition and arrangement.

1265 The ESSU concept deals with crop diversification
 1266 for agroecology, aiming to conceptually equip scien-
 1267 tists working on intercropping and agroforestry systems.
 1268 Agronomists have useful suites of scale concepts (plant,
 1269 stand, plot/field and farm) and technical concepts (techni-
 1270 cal management sequence, cropping system, and farming
 1271 system) that integrate technical management at different
 1272 scales. Focusing on plant and animal taxonomy (e.g., spe-
 1273 cies names and varieties), plant and animal status in the
 1274 agroecosystem (e.g., crops, service plants, weeds, cattle,
 1275 and pest controllers), and the species spacing design and
 1276 density per soil surface unit, the proposed ESSU con-
 1277 cept is both a complementary scale concept larger than
 1278 the plant scale and a complementary technical concept
 1279 describing the species interactions and the TES they pro-
 1280 vide. We propose a graphical representation of the ESSU
 1281 (see figures in Sections 4 and 5) to operationalize the use
 1282 of the concept.

1283 In applying the ESSU concept to diversified agroeco-
 1284 systems, we demonstrated its relevance and suitability to
 1285 represent temporal changes over 1 year (pruning of shade
 1286 trees), across several years (changing inter-row manage-
 1287 ment in a vineyard/orchard), and over decades (agroeco-
 1288 system trajectory of diversification from an initial to a
 1289 final cropping system), indicating its generalizability and
 1290 flexibility. The user of the ESSU concept must decide the
 1291 level of complexity required to build and adapt ESSU to
 1292 meet their own objectives and TES. Because the ESSU
 1293 concept allows both on/off and gradual representations of
 1294 a TES provision area, we recommend integrating gradients
 1295 of TES provision into ESSU when required (e.g., biologi-
 1296 cal control of pests by insects or other animals).

1297 The ESSU concept opens new research avenues for
 1298 the study of diversified agroecosystems based on the
 1299 ESSU concept. The ESSU concept also has a wide range
 1300 of applications for researchers, farmers, and agricul-
 1301 tural advisers dealing with the biological complexity of
 1302 diversified agroecosystems. They can use it as a dialog
 1303 and representation tool, like Masure et al. (2022). The
 1304 ESSU is relevant for prioritizing views of analysis and
 1305 for avoiding misunderstanding and misinterpretation of
 1306 agroecosystem functioning. It can be used for (i) the (co)
 1307 design of more efficient agroecological systems according
 1308 to the TESs; (ii) rapid audit, evaluation, and monitoring
 1309 of farming practices for diversity/resilience across large
 1310 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 tran-
 sition to highly diversified agriculture.

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Authors' contributions SR: original idea, supervision, conceptual-
 ization, writing of definition and designing sections, of oil palm and
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 abstract, review and editing, figures 1–3abcd–4ab–5abc–6–7–8–9–10,
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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 edit-
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JG: conceptualization, writing of initial modeling section, review
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FR: conceptualization, writing of initial modeling section, review
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SS: conceptualization, writing of cocoa example, review and edit-
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GNC: review and editing of last versions of the paper, writing of
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EJ: supervision, conceptualization, writing of single stratum inter-
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Declarations

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