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Abstract	Duru et al. (Agron Sustain improving the performance response, this paper propo- ecosystem services, in intr- unit called ESSU, encomp- trees, livestock, spontaneed patches, and eventually ar ESSU concept allows repr- spatial unit that provides to represents. It can then be agroecological systems ac practices for biodiversity/ Development Goal 2 targe agroecosystems using a m spacing design. We demo of diversified agroecosyst tree agroforestry systems, representing temporal cha generalizability and flexit avenues for the study of d practices, biodiversity, an knowledge gap about rela	n Dev 35:1259-1281, 2015) highlighted a missing tool for studying and ce of cropping systems in the transition to highly diversified agriculture. In oses a concept for designing, modeling, monitoring, and auditing desired ercropping and agroforestry systems. This concept delimits the smallest spatial passing all the interacting species and other functional components (e.g., crops, ous vegetation, semi-natural habitats such as hedges, ditches, and forest nimals) that together provide a specified set of ecosystem services. The novel resentation of an entire diversified agroecosystem by the repetition of the the same sets of targeted ecosystem services as the agroecosystem it used for various activities, such as the (i) design of more efficient coording to the targeted ecosystem services; (ii) rapid audit of farming resilience across large tracts of farmland as part of achieving Sustainable ets of sustainable food production systems; and (iii) modeling such diversified notif adapted to represent the targeted ecosystem services and the species nstrate that the ESSU concept is highly flexible and applicable to a wide range ems, with applications for arable intercropping, crop-tree intercropping, tree- and agro-sylvo-pastoralism. We also show its relevance and suitability for inges over 1 year, across several years, and over decades, indicating its bility. We argue that ESSU could open new theoretical and practical research tiversified agroecosystems. Considered with all the knowledge available on d ecosystem services, ESSU might provide a learning-support tool to fill the tionships among practices, biodiversity, and associated ecosystem services.
Keywords (separated by '-')	Agroecolgy - Ecosystem s	services - Intercropping - Agroforestry - SDG 2

Footnote Information

REVIEW ARTICLE

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

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⁷ Accepted: 10 May 2023

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9 Abstract

10 Duru et al. (Agron Sustain Dev 35:1259-1281, 2015) highlighted a missing tool for studying and improving the perfor-11 mance of cropping systems in the transition to highly diversified agriculture. In response, this paper proposes a concept 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-14 tional components (e.g., crops, trees, livestock, spontaneous vegetation, semi-natural habitats such as hedges, ditches, 15 and forest patches, and eventually animals) that together provide a specified set of ecosystem services. The novel ESSU 16 concept allows representation of an entire diversified agroecosystem by the repetition of the spatial unit that provides 17 the same sets of targeted ecosystem services as the agroecosystem it represents. It can then be used for various activities, 18 such as the (i) design of more efficient agroecological systems according to the targeted ecosystem services; (ii) rapid 19 audit of farming practices for biodiversity/resilience across large tracts of farmland as part of achieving Sustainable 20 Development Goal 2 targets of sustainable food production systems; and (iii) modeling such diversified agroecosystems 21 using a motif adapted to represent the targeted ecosystem services and the species spacing design. We demonstrate that 22 the ESSU concept is highly flexible and applicable to a wide range of diversified agroecosystems, with applications for 23 arable intercropping, crop-tree intercropping, tree-tree agroforestry systems, and agro-sylvo-pastoralism. We also show 24 its relevance and suitability for representing temporal changes over 1 year, across several years, and over decades, indi-25 cating its generalizability and flexibility. We argue that ESSU could open new theoretical and practical research avenues 26 for the study of diversified agroecosystems. Considered with all the knowledge available on practices, biodiversity, and 27 ecosystem services, ESSU might provide a learning-support tool to fill the knowledge gap about relationships among 28 practices, biodiversity, and associated ecosystem services.

²⁹ Keywords Agroecolgy · Ecosystem services · Intercropping · Agroforestry · SDG 2

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53 1 Introduction

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

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



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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 91 can also be implemented "through time in the same unit 92 of space" like in arable cropping systems (e.g., crop rota-93 tion) and in tree-based agroecosystems (e.g., agroforestry 94 trajectories; Jagoret et al. 2018). Both spatial and temporal 95 dimensions of crop diversification are often intertwined, as 96 evidenced by the evolution of different vegetation strata in 97 complex systems such as cocoa-based agroforestry systems 98 (Jagoret et al. 2011; 2017; Deheuvels et al. 2012). Species 99 diversification in space and time is used to provide and 100 enhance ecological processes that support multiple ecosys-101 tem services (Garcia et al. 2018; Nijmeijer et al. 2019). Like-102 wise, field management techniques and spatio-temporal pat-103 terns of plant species assemblages can be used as levers to 104 reduce the dependence on chemical inputs and fossil energy 105 by providing ecosystem services (Gurr et al. 2003; Swift 106 et al. 2004; Médiène et al. 2011). These examples underline 107 that biotic and abiotic interactions within the agroecosystem 108 can be managed in ways that confer robustness, resilience, 109 and sustainability to agroecosystems while reducing the use 110 of external inputs and their associated negative externalities. 111

We hypothesize that diversified agroecosystems can be 112 analyzed and represented by the ecosystem services cascade 113 framework (Fig. 2). In this framework, ecosystem services 114 are defined as contributions that ecosystems make to human 115 well-being (Haines-Young and Potschin 2010; 2016; 2018) 116 and result from a cascade of ecological processes and eco-117 system functions. Ecological "processes" define how liv-118 ing organisms perform specific activities in the ecosystem 119 and interact with their biotic and abiotic environments. In 120 contrast, "functions", usually resulting from a combination 121 of processes indicate the capacities or capabilities of the 122 agroecosystem to realize something potentially useful to 123 people and also to agroecosystem functioning itself (Haines-124 Young and Potschin 2010; 2016; 2018). Both processes and 125 functions depend on the spatial structure of the ecosystem 126 and may be strongly determined by species composition, 127 diversity (Balvanera et al. 2006; Diaz et al. 2007; Lavorel 128 et al. 2013), and management (Quétier et al. 2007; Médiène AQ2 9 et al. 2011; Duru et al. 2013). Ecosystem services give rise 130

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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).



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

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 ecosys- tems*;
- regulation and maintenance services, that is, *mediation or moderation of the ambient environment by living organ*

isms or non-living processes that affect human wellbeing; and 148

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



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the diversified agroecosystems.



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-

management practices can deliver a set of TES in givenconditions.

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

However, Duru's et al. (2015) review article suggests "adoubly challenging research agenda for the development of

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

(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:

- 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
- be used as a learning-support tool for assessing complex and adaptive agroecosystem dynamics.

Based on very recent and ongoing investigations, this 204 paper proposes a unified definition of a concept developed 205 in recent investigations (Rafflegeau et al. 2019; Masure 206 et al. 2022, 2023) for designing, modeling, and auditing 207 desired ecosystem services in diversified agroecosystems. 208 As a definition, the concept delimits the smallest spatial unit 209 encompassing all the interacting species and other functional 210 components (e.g., crops, trees, livestock, spontaneous veg-211 etation, semi-natural habitats such as hedges, ditches, and 212 forest patches) that together provide a specified set of eco-213 system services represented in a farming landscape. We have 214

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

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 agro-239 nomical concept corresponding to the computer science con-240 cept of a simplified scene of the system when modeling a 241 diversified agroecosystem. Secondly, agronomists do not use 242 a concept to represent a whole system integrating cultivated 243 species, spacing design, technical management, the TES, and 244 their provision areas, which are necessary for designing diver-245 sified agroecosystems. Thirdly, we need to represent and com-246 pare agroecosystems when auditing the TES they provide, and 247 ESSU could be the simplified representation of the system. 248

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

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 267 originality and strength of the ESSU concept are based on 268 its capacity to implement the following activities: describe, 269 design, monitor, and model a wide range of intercropping 270 and agroforestry systems that support TES. In the following 271 sections, we define and describe the ESSU and its applica-272 tions in a wide range of diversified agroecosystems using 273 the ESSU concept to illustrate its value. We then discuss 274 other uses of the concept such as supporting the design of 275 experimental protocols, agroecosystem functioning models, 276 optimized cropping systems, and as a monitoring and evalu-277 ation tool. We conclude by identifying the limits of ESSU. 278

2 The concept of ecosystem services 279 functional spatial unit 280

2.1 Description

The ESSU definition given in the introduction relies on two 282 propositions. First, diversified and multifunctional agro-283 ecosystems can be considered as the spatial repetition of 284 elementary units, so that it is useful to delimit the smallest 285 repeated spatial unit. Secondly, in agroforestry systems, 286 we already know the ecosystem services provided by all 287 the interacting species and other functional components. 288 Following our definition, the same properties characterize 289 an ESSU and the agroecosystem it is representing. When 290 interactions are expected between two or more spatial units, 291 such as when a TES is located between two spatial units, 292 then these two spatial units are part of the same ESSU. The 293 properties that the ESSU concept focuses on are plant and 294 animal taxonomy (e.g., species names and varieties), plant 295 and animal status in the agroecosystem (e.g., crops, ser-296 vice plants, weeds, biological pest controllers, and cattle), 297 plant development in space and time (e.g., size, stratum, 298 perennial or annual, and age), animal population dynamics 299 for pest control, the plant spacing design, and the animal 300 density per hectare. For these reasons, the ESSU is at a 301 larger scale than the plant and animal but smaller than the 302 field/farm/territory, with its scale determined by the larg-303 est TES provision area. The ESSU concept complements 304 agronomists' scale concepts (plant, stand, field, farm, and 305 territory) and their technical concepts (plant techniques 306 like pruning, technical management sequence, cropping 307 system, farming system, farm functioning) that integrate 308 the technical management at different scales (Doré et al. 309 2006). Specifically, the ESSU concept is both (i) a com-310 plementary scale for agronomists by providing the smallest 311 spatial unit encompassing the spacing design of the species 312 in their relative proportions in the agroecosystem; and (ii) 313 a technical concept formalizing the technical management 314 of species interactions that provide TES. 315



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In intercropping systems based on arable crops, Justes 316 et al. (2021) show the links between field management prac-317 tices (including inter-row and within-row spacing, location 318 of uncultivated habitats) and harvesting strategies of main 319 crops (separate harvests, full harvesting with direct use, 320 and full harvesting with cleaning or sorting before use) for 321 explaining different performance outcomes of intercropping. 322 Consequently, the area where each TES is provided results 323 from the choices of field management and harvesting strat-324 egies. Thus, the ESSU can change according to farmers' 325 management decisions. 326

Diversified agroecosystems consisting of perennial crops 327 may evolve over years or decades because the life cycle of 328 perennials implies a succession of "young" (unproductive), 329 "mature" (productive), and "senescent" (low production) 330 stages. Also, farmers may change their cultural practices 331 because of newly acquired knowledge and/or the progressive 332 introduction of improved technologies. The life cycle changes 333 of perennials can result in TES changing in stages or gradu-334 ally. TES could change in steps through time punctuated with 335 periods of stability. However, smallholder farmers typically 336 rejuvenate old cocoa agroforestry systems gradually, often 337 tree-by-tree, rather than rejuvenating their whole plot at one 338 time (Jagoret et al. 2017). In both cases, an ESSU can accom-339 modate different development stages in the same agroecosys-340 tem as well as accommodating changes in TES over time. 341

The concept of ESSU integrates the characteristics of 342 the species mixtures interacting in and making use of the 343 same space such as livestock, spontaneous below and above-344 ground flora/fauna, and their dynamic interactions over 345 time. Depending on species architectures (above and below-346 ground) and temporal development, the ESSU can be single-347 stratum or multi-strata. It includes the corresponding biotic 348 and abiotic conditions, and interactions between species and 349 other living organisms in the spatial unit. In agroecosystems 350 managed by farmers, the composition of species and the spa-351 tial arrangement of plants or groups of the same plants in the 352 plot and their temporal evolution are of fundamental signifi-353 cance for describing, analyzing, and representing the func-354 tions provided by the ecosystem. The concept of ESSU could 355 pave the way to modeling both existing and newly designed 356 intercropping and agroforestry systems more generally, by 357 simplifying them into ESSU which provide sets of TES. 358 When auditing the different TES provided by different agro-359 ecosystems or by transitioning agroecosystems, the ESSU 360 concept could provide a relevant scale for comparisons. 361

362 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. 367

Identifying an ESSU requires identifying a set of desired 368 ecosystem services to form the TES (not all ecosystem services 369 will be desired and become part of the TES). Then, the TES 370 are identified as well as the time scale and the species assem-371 blage needed to provision these TES. The ESSU should rep-372 resent the smallest spatial unit that includes all the species and 373 the corresponding area required to provide the TES. The agro-374 ecosystem species spacing design determines TES provision 375 areas. The ESSU encompasses these areas and all the species 376 in their field relative proportions. To determine the ESSU area, 377 we recommend starting with the TES provided by the species 378 with the lowest density (e.g., shade trees in coffee or cocoa 379 agroforestry systems, trees in alley cropping systems), once the 380 relative field proportions of species are known. Indeed, the size 381 of the ESSU depends on the largest TES provision area, often 382 provided by the species with the lowest density. 383

In addition, the TES are mostly the outcome of interac-384 tions between species. Consequently, plant scales are usually 385 irrelevant to describe TES provided by diversified agroeco-386 systems because the plant scale does not take into account 387 the distance between species. Yet, the area provisioning a 388 particular TES can be smaller than the plot (e.g., a few square 389 meters can provide the biomass production service). How-390 ever, some TES can be provided only at a wider scale than 391 the plot as the functions subtending them occur outside the 392 plot as edge effects (e.g., biological regulation services linked 393 to semi-natural habitats such as hedges, ditches, and forest 394 patches). In such cases, the ESSU will encompass the semi-395 natural habitat and may be useful for landscape design, mod-396 eling, monitoring, or auditing (within one or more farms). 397

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 sys-
tems. 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.401
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3.1 Single stratum intercropping systems

Intercropping systems based on arable crops are single stra-
tum diversified agroecosystems. For each of the four exam-
ples considered in Fig. 3, we identified an ESSU correspond-
ing to a set of TES.408
410411411

In single stratum cereal/legume mixtures, herbaceous 412 legumes can be mixed with cereal plants, in the same row 413



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

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

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



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. 447 448

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 452 453 454 455 456 457 458



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 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.



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mineralization, food web structure increasing nematode den-459 sities and detritivorous microarthropod densities (Sauvadet 460 et al. 2018), and soil structure by increasing rainfall infiltra-461 tion (Meylan et al. 2017). Moreover, shade provided by E. 462 poeppigiana changes the microclimate, which has a direct 463 impact on coffee pest and disease dispersion and develop-464 ment (Allinne et al. 2016; Avelino et al. 2018). Microcli-465 mate regulation (temperature, humidity, and radiation) also 466 induces changes in coffee tree physiological development 467 and yield component allocation (Charbonnier et al. 2017). 468 All these biophysical mechanisms interact (Andres et al. 469 2016) to generate various ecosystem services at the Eryth-470 rina shade tree scale: two of regulation (pest and disease 471 control, soil erosion); one of support (nutrient cycling); and 472 one of provision (coffee yield). 473

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, 492

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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. 489

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 494 vineyards with crops or service plants in the inter-rows. 495

The design of agroecosystems based on fruit trees in rows, 496 together with low stratum service plants in the inter-row 497 (e.g., cover plants, flower strips, legumes, and deep-rooted 498 plants), provides various ecosystem services (Albert et al. 499 2017; Demestihas et al. 2017; Lauri and Simon 2019; Pitch-500 ers et al. 2021; Simon et al. 2017). In the inter-row, service 501 plants enhance pollination and biocontrol by hosting preda-502 tors or repelling plant enemies (e.g., Rosmarinus officinalis, 503 Tagetes patula in temperate orchards, and Musa spp. in tropi-504 cal cocoa-based plantations). They also provide supporting 505 ecosystem services such as nitrogen cycling (e.g., by Cajanus 506 cajan, Desmodium intortum, and Phaseolus vulgaris in cocoa 507 and coffee-based plantations), and water cycle regulation, 508 that includes water flow maintenance and water quality 509 protection, both being tightly related to erosion control and 510



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.



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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-

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 sys-516 517 tems based on alley-cropping (e.g., timber tree rows with spacing allowing mechanized production of the crops in 518 the alleys between tree rows). Three types of vegetation 519 strata can be identified, each one providing a TES: the high 520 strata trees (main TES, wood production); the crop, pos-521 sibly including medium strata trees (main TES, food or 522 523 feed production); and the understory vegetation strip (main TES, refuge for plant diversity, natural habitats for benefi-524 cial arthropods, carbon storage; see Boinot et al. (2019)). 525 526 Thus, the ESSU encompasses all three or more strata in their respective densities, and contains the whole gradient of 527 interactions between the three elements. Due to the potential 528 anisotropies in these interactions (e.g., with east-west tree 529

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.

rows, the crop in the north part of the crop alley experiences 530 different growing conditions to the crop in the south part 531 of the alley; Inurreta-Aguirre et al. 2018), the ESSU also 532 encompasses both alley half-sides of the tree row. With a 533 single species of timber tree, the ESSU encompasses only 534 one tree. If several timber species are mixed within the tree 535 row, the ESSU extends to encompass all the tree species 536 along one line to reflect the same relative densities of each 537 tree species along the whole line (Fig. 5b). If different spe-538 cies of trees are planted over different lines (Fig. 5c), the 539 ESSU encompasses several tree rows in the same frequency 540 as in the whole plot. 541

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 546





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,

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

563 3.2.4 Highlights of Section 4

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

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

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

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 agroecosystems, for modeling and designing intercropping and agroforestry systems. 588

4.1 Auditing ecosystem services provision 589 in diversified agroecosystems 590

4.1.1 The ESSU concept: an appropriate scale for auditing ecosystem services provision 592

Complex systems raise the question of how they can be char-593 acterized, described, and compared for auditing ecosystem 594 service provision by different agroecosystems. In the case 595 of heterogeneity induced by the structure of the vegetation 596 association, the ESSU makes it possible to identify the 597 smallest scale at which it is appropriate to measure vari-598 ables for cropping system analyses and construct assessment 599 indicators (see Masure et al. 2022 for how this concept was 600 used to review oil palm agroforestry systems worldwide). 601

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 608

 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 Regular spacing Irregular spacing	Square or rectangular Triangle Irregular	Square or rectangular Hexagonal Irregular



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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 small- est 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 stand- ard 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

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

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 614 tool for auditing ecosystem service provision across agro-615 forestry systems, and can also indirectly help the develop-616 ment of analytical tools, representations, and indicators use-617 ful for auditing. The concept facilitates easy comparisons 618 of the provided TES across different agroforestry systems 619 and enables determination of the diversity and frequency 620 621 of the TES provided, all important for auditing ecosystem services provision. This capacity to audit ecosystem services 622 provision and monitor their change in response to develop-623 ment interventions is becoming increasingly important in 624 the context of the UN's Sustainable Development Goal 2, 625 Target 2.4 (see Section 2). ESSU is a tool for establishing AQ3 baselines in ecosystem service provision and for assessing 627 progress towards Target 2.4 in terms of improved resilience 628 of agricultural systems and strengthened adaptive capacity. 629

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

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

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 647 1) in the vineyard, maintaining spontaneous (or sowing) 648 selected service crops in grapevine inter-rows can provide 649 multiple ecosystem services (Garcia et al. 2018). Here, we 650 provide examples of three different TES: erosion reduc-651 tion (Fig. 7; TES 2); soil fertility improvement from green 652 manure (Fig. 7; TES 3); and biological control of pests 653 (Fig. 7; TES 4). Erosion occurs mainly in grapevine inter-654 rows as preferential corridors for water runoff (García-Ruiz 655 2010). Moreover, technical management of inter-rows is 656 the main lever to reduce water runoff and soil erosion in 657 vineyards, and partially depends on the composition of 658 inter-row plant communities and their functional structure 659 (e.g., Garcia-Ruiz et al. 2010). Consequently, it is appropriate to limit the scope of the erosion reduction TES to the 661 inter-row scale. The soil fertility improvement TES may 662 involve the grapevine row, as the manure is anticipated to 663 improve production of the main crop. Here, the inter-row 664 management may be the main lever to improve soil fertil-665 ity with service crops like cover crops, but some species 666 that grow in the grapevine row may compete with grape-667 vines for soil nutrients. Therefore, the appropriate provi-668 sion area for soil fertility improvement from green manure 669 TES would include a vineyard row and the two adjacent 670 half-inter-rows. 671

The provision area for the biological control of pests 672 TES includes the vineyard's surrounding vegetation (Fig. 7; 673 complex field margin), because species diversity is deter-674 mined both by service crops inside the field (e.g., Burgio 675 et al. 2016) and habitats outside the field (Landis et al. 2000; 676 Rusch et al. 2016). Distance from agroecological infrastruc-677 tures (edge effects) is also important for the level of biologi-678 cal control of pests by insects or other animals (e.g., Thom-679 son and Hoffmann 2013). In Fig. 7 example, we represent a 680 situation where the provision area for the biological control 681 of pests is gradually decreasing from the agroecological 682 infrastructure and limited to six rows. This gradient of bio-683 logical regulation provision area can be adjusted to the popu-684 lation dynamics of the species controlling the pests. The 685 ESSU corresponding to the set of TESs 1 to 4 is a rectangle 686





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

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, 692 the provision area for the TES of biological control of 693 pests (Fig. 7; TES 5) is limited to a specified distance from 694 695 the complex field margin (e.g., Boinot et al. 2019; Cordeau et al. 2012). Its extent determines the shape of the ESSU 696 for this part of the field, including the TES provision area 697 698 for annual crops production (Fig. 7; TES 6) and niche complementarity for nitrogen resources (Fig. 7; TES 7). 699 In the field of annual crops sown in strip intercropping, 700 both the complex field margin and the strips of unculti-701 vated habitats provide complementary and independent 702 gradients of biological control of pests. The uncultivated 703 704 strips are optimally located in relation to the field margin and from each other to provide some level of biological 705 control of pests everywhere in the field (Fig. 7 TES 5). In 706 this field, the ESSU gathering TES 5 to 7 is 1m wide and 707

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.

encompasses the complex field margin, all the rows of 708 single crop and both strips of uncultivated habitats. 709

Integrating surrounding agroecological infrastructures 710 such as windbreaks, hedges, riparian forest, and riparian 711 buffer strips (i) enables scaling-up of the ESSU; and (ii) 712 implies choosing a threshold for provision of biological con-713 trol of pests by insects and other animals. More generally, 714 we illustrate that the ESSU concept is (i) applicable from the 715 plant to the landscape scale and (ii) accommodates spatial 716 gradients of intensity of provision of particular TES. When 717 juxtaposed ESSU are identified at the landscape level, there 718 is no interaction between them by definition (Fig. 7). If an 719 interaction is perceived between two ESSU, then they are 720 not correctly identified. 721

4.2.1 The ESSU concept: a tool for auditing TES provision 722 during the evolutionary path of an agroecosystem 723

While an ESSU figure at a given time represents the species724spatial arrangements and the TES they provide, several ESSU725figures can represent the evolutionary path of an agroecosystem.726



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

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

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

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

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

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; 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.



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farmers introduce cocoa and fruit trees while retaining some 778 self-seeded forest trees. 779

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

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 801 agroforestry systems. 802

4.3 Modeling diversified agroecosystems using 803 the ESSU concept 804

4.3.1 Why is ESSU a useful concept for modelers?

Modeling is the conceptualization and representation of a 806 phenomenon, process, or complex system in mathematical 807 terms, which can then be implemented by numerical code in 808 software algorithms. Modeling is widely used in agronomy 809 to represent the cropping system functioning and predict 810



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.



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

topological terms, that is, the connections between neighbor-
ing 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).845
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Thus, the ESSU concept should be a familiar and useful 849 concept for modelers, as they have been using it for years-850 see examples below-without having a single term to name 851 it. In this respect, using a common name for the ESSU 852 concept might enhance communications, interactions, and 853 synergies between field scientists (agronomists, sensu lato, 854 and ecologists) and computer modelers, studying vegetation 855 dynamics and field trial design. 856

4.3.2 Examples of model spatial domain definition using the ESSU concept

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



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

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

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

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of crop production and temperature regulation), and defined917the scene as the ESSU for these TES. The ESSU corresponds to the two species represented by half the canopy918of one species, a half-canopy of the other species, and the920inter-row distance between them. Other spatial aspects were921neglected (e.g., spatial niche complementarity between root-922ing patterns of species).923

4.4 Designing diversified agroecosystems

The ESSU concept can also be used as a generic tool for 925 designing intercropping systems with farmers. When design-926 ing intercropping systems, agronomists are used to consid-927 ering various key components simultaneously: field and 928 machinery constraints, the TES, the species, and their spatial 929 and temporal arrangements (Bedoussac et al. 2015; Justes 930 et al. 2021; Stomph et al. 2020). Thus, they are familiar with 931 some aspects of the ESSU concept. For agronomists, the 932 novel part of the concept is that the ESSU is based on the 933 smallest spatial unit to be designed to represent the system. 934 On the basis of how we have planned to design agroecosys-935 tems in several ongoing projects, we formulate hypotheses 936 on the questions that a designer would have to consider to 937 use the ESSU concept during a design process. As a result, 938 we suggest the following four steps for designing diversified 939 agroecosystems. The three steps design process proposed by 940 Gaba et al. (2015) for developing sustainable multiple crop-941 ping systems are included in steps 2 and 3 of our proposition. 942

Step 1: Consider all constraints and available means for 943 managing the future agroecosystem according to the 944 farmer's production objectives, both at the farm and at 945 the plot scales. The farm structure, labor availabilities, 946 and the machinery for both the field management prac-947 tices and the post-harvest product transformation must 948 be considered in the design of the spatial arrangement 949 within the plot (Meynard 2012; Simon et al. 2017). For 950 example, combine harvester and sprayer widths are key 951 factors influencing the spatial design of timber tree rows 952 inside arable plots (Dupraz and Liagre 2008). 953

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 954 ESSU is defined with regard to the provision of a set of 955 TES provided simultaneously or successively during the 956 different phases of the intercropping system, according to 957 the farmer's objectives and local environment. For exam-958 ple, farmers currently design most cocoa-based agrofor-959 estry systems in the Caribbean (Notaro et al. 2020; 2021; 960 2022) by first targeting ecosystem services relying on the 961 provision of annual crops and plantains, as well as soil 962 fertility improvement during the unproductive phase of 963 the cocoa tree. As soon as the cocoa tree canopy closes 964 and the first pods are being produced, the farmer will 965 cease annual cropping and gradually reduce plantain pro-966 duction while new TES are included, such as cocoa and 967 fruit production, as well as new management techniques 968 for pests, diseases, and pollinating insects. 969

Step 3: Identify requirements for species diversity and 970 spatio-temporal structures to provide the TES. The diver-971 sity of cropped species and their spatial arrangement is 972 of crucial importance for the provision of TES. The spa-973 tial arrangement (distances between plants) and topology 974 should take account of the interactions between species. 975 This is to minimize adverse effects such as allelopathy 976 and competition for resources, and to increase positive 977 effects like pest deterrence and improved water infiltra-978 tion. The management of the plot through time must also 979 be considered for agroforestry systems. It should take into 980 account the evolution of inter- and intraspecific interac-981 tions such as rising tree-crop competition with tree age. In 982 the most abstract approach, a TES can be defined without 983 referring to particular species by using functional traits. 984 Translation of the prototypal ESSU into practical imple-985 mentation such as selection of species and cultivars and 986 precise mapping of the plot can be done afterwards. 987

Step 4: Determine the ESSU and replicate it throughout 988 the plot area. By relying on existing knowledge of plant 989 interactions, an ESSU can be designed for each develop-990 ment phase of the agroecosystem and its corresponding 991 TES. The ESSU can be drawn as the simplest selection of 992 interacting plants (various species) and habitats capable 993 of providing the set of TES, in space and time. Then, the 994 ESSU can be modified to accommodate changing farm-995 ing strategies or agroecosystem structures, for example, 996 in relation to tree growth. 997

998 4.4.1 Highlights of Section 5

999 • 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 agroeco-systems. 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 1008 evolutionary path of an agroecosystem and to compare 1009 different pathways in transitioning agroecosystems. We 1010 found it useful to describe the changes in the manage-1011 ment of crops, in crop succession or in farmers' changing 1012 production strategies and priorities. This concept allows 1013 simple representations of evolution in the TES provided 1014 by an agroecosystem. It allows consideration of the trade-1015 offs between TES associated with different strategies of 1016 agroforestry transition and other contextual factors like 1017 land pressure and smallholder labor availability. 1018
- Delimiting an ESSU also permits a reduction in the 1019 complexity when modeling TES provision by agrofor-1020 estry or intercropping systems. The concept is compat-1021 ible with the formalisms of Hi-sAFe 3D, WaNuLCAS 1022 2D, and STICS 1D soil-crop models, notably for scene 1023 and boundary definition. The ESSU concept should be 1024 a familiar and useful concept for modelers, as they have 1025 been using it for years without having a single term to 1026 name it. 1027
- Delimiting and replicating an ESSU can also be key 1028 final steps for designing a diversified agroecosystem. 1029 This would be done when all constraints, resources, and 1030 ecological processes have been identified and farmers' 1031 objectives have been reformulated as a set of TES. When 1032 designing cropping systems, agronomists are accustomed 1033 to considering the defining elements of the ESSU con-1034 cept; what would be new to them is that its design is 1035 based on the smallest spatial unit possible. 1036

5 Novelty, genericity, and limits of the ESSU concept 1037

The ESSU concept relies on the two propositions presented 1039 in Section 3. Concerning the first proposition, we showed 1040 in Section 4 that for a wide range of diversified agroecosys-1041 tems, each agroecosystem can be represented as a repeti-1042 tion in space of the ESSU, constituting the smallest spatial 1043 unit encompassing all the species and the TES provided. 1044 In Section 5, we explained that because the ESSU repre-1045 sented all the same TES as the agroecosystem it reflected, 1046 it could therefore be used for designing, modeling, or audit-1047 ing agroecosystems. Concerning our second proposition 1048 that we already know, the ecosystem services provided by 1049 interacting species and other functional components dem-1050 onstrate that our concept builds on an extensive literature 1051 about ecosystem services provided in intercropping and 1052 agroforestry systems (see, for example, the special issue of 1053 papers from around the world on the ecosystem services 1054



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and environmental benefits provided by agroforestry—Jose2009).

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

1089 5.1 Novelty of the ESSU concept

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



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TES, and that diversity patterns within a field plot determine1106them. They define a new scale of analysis and management1107between the levels of plant and plot. By doing so, ESSU also1108highlights the idea that spatio-temporal patterns of organ-1109isms are essential components of diversity in the functioning1110of agroecosystems. Thus, the ESSU concept offers an effec-1111tive method for accommodating complexity.1112

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

5.2 Generalizability of the ESSU concept

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

rectangle including this species and the next cultivated 1157 row or strip-see Fig. 4). Generic forms of ESSU (of dif-1158 ferent sizes, though) can be defined for any given type 1159 of TES if the agroecosystems share similar diversity pat-1160 terns. Such genericity should enable analytical compari-1161 sons between agroecosystems, standardize methods, and 1162 help design generic modeling modules that can be param-1163 eterized for each type of agroecosystem. Thus, the ESSU 1164 concept provides an efficient tool for agroforestry design 1165 and rapid monitoring and evaluation of TES over large and 1166 diverse landscapes. 1167

We mentioned in the introduction that the ESSU con-1168 cept is dedicated to various users (researchers, farmers, 1169 and agricultural advisers) dealing with the biological 1170 complexity of diversified agroecosystems, for different 1171 uses (design, model, audit). The richness of our concept 1172 comes from its ability to integrate the diversity of species 1173 and the TES they provide into a spatial unit. This spatial 1174 unit is concretely present in a crop model, but also in the 1175 field where it can even be delimited. The flexibility of 1176 our concept comes from the fact that its graphical rep-1177 resentations are easily explicable, usable as tools of rep-1178 resentation (Masure et al. 2022) and for dialog between 1179 actors. Thus, if it is obvious that researchers will repre-1180 sent diversified agroecosystems in models, they will be 1181 able to collect information and render it to farmers and 1182 agricultural advisers by mobilizing our concept and its 1183 graphic representations. The same is true among users of 1184 the concept for its other uses. Once known, the simplicity 1185 of use of our concept could also allow farmers themselves 1186 to represent their diversified agroecosystems or design 1187 prototypes to other actors. 1188

1189 5.3 Limits and perspectives

The ESSU formalizes the way species diversity is repre-1190 sented in space and time within agroecosystems by farmers 1191 to achieve TES provision objectives. Currently, as proposed 1192 here, it focuses on species taxonomy (e.g., species names 1193 and varieties) and status (e.g., crops, service plants, weeds, 1194 cattle, and pest controllers), the species development in time 1195 and space (e.g., size, stratum, age and animal population 1196 dynamic), and the species spacing design and density per 1197 unit of soil surface. This approach is highly relevant as it 1198 reflects how farmers and stakeholders generally deal with 1199 species diversity. However, ecological research increasingly 1200 reveals that plant functional traits rather than taxonomy 1201 strongly influence most ecological processes underlying 1202 ecosystem services. It also shows that farmers have a rel-1203 evant perception of, and sometimes explicitly manage, trait 1204 diversity in agroecosystems (Garnier et al. 2016; Isaac et al. 1205 2018). The ESSU concept could be developed further to pro-1206 vide a mechanistically sound approach for analytical, design, 1207

and modeling work by incorporating plant trait patterns into 1208 ESSU (e.g., the zone of influence of species), or even by 1209 building ESSU from trait distribution within agroecosys-1210 tems. Additionally, the current ESSU concept hypothesizes 1211 that plant species associations are the primary drivers of 1212 TES. However, it recognizes that a range of other living, 1213 sometimes "hidden," organisms from different trophic lev-1214 els may play an active if not pivotal role (e.g., soil fauna 1215 and micro-organisms for services related to biogeochemical 1216 cycles) (Deheuvels et al. 2014; Rousseau et al. 2012). More 1217 comprehensive knowledge of how the interaction network 1218 among all involved organisms is structured and evolves 1219 through time in agroecosystems would refine the 3D size, 1220 geometry, and dynamics of ESSU. 1221

As proposed here, the ESSU does not account for the 1222 impacts of environmental heterogeneity (e.g., soil hetero-1223 geneity and slope) and adaptive management by farmers 1224 of species interactions and ecological processes underly-1225 ing TES. Using ESSU to design the "best" association of 1226 species and habitats would define a potential TES rate, 1227 but the actual TES rate will be regulated by how farm-1228 ers manage the ESSU in interaction with environmen-1229 tal conditions. Indeed, in heterogeneous environments, 1230 farmers may adapt their management strategy locally and 1231 express differently how a given ESSU will contribute to 1232 TES. On this basis, an agroecosystem could be concep-1233 tualized as several "in practice" versions of one ESSU, 1234 resulting from variations around a given set of species 1235 associations, environmental conditions, and management 1236 strategies. Defining "adjustable" farming practices rel-1237 evant to TES would strengthen the ESSU concept. For all 1238 these reasons, the ESSU concept could contribute from 1239 a methodological point of view to the main challenge 1240 highlighted by Gaba et al. (2015) expressing an urgent 1241 need for the transition towards a more sustainable agri-1242 culture, clearly based on the functional links between 1243 species diversity, associated agricultural management, 1244 and the provided TES. 1245

6 Conclusion and prospects

The ecosystem services functional spatial unit (ESSU) 1247 concept is a representation of in situ diversified agro-1248 ecosystems and the targeted ecosystem services (TESs) 1249 they provide. We demonstrated that the ESSU concept is 1250 highly flexible and applicable to a wide range of diversi-1251 fied agroecosystems, with applications for arable inter-1252 cropping, crop-tree intercropping, tree-tree agroforestry 1253 systems, and even agro-sylvo-pastoralism by including 1254 animals. When an ESSU is identified, it represents the 1255 smallest spatial unit to consider at a given time for the 1256 study of the TES provided by the species composition and 1257



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

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

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

The ESSU concept opens new research avenues for 1297 the study of diversified agroecosystems based on the 1298 ESSU concept. The ESSU concept also has a wide range 1299 of applications for researchers, farmers, and agricul-1300 tural advisers dealing with the biological complexity of 1301 diversified agroecosystems. They can use it as a dialog 1302 and representation tool, like Masure et al. (2022). The 1303 ESSU is relevant for prioritizing views of analysis and 1304 for avoiding misunderstanding and misinterpretation of 1305 agroecosystem functioning. It can be used for (i) the (co) 1306 design of more efficient agroecological systems according 1307 to the TESs; (ii) rapid audit, evaluation, and monitoring 1308 of farming practices for diversity/resilience across large 1309 tracts of farmland as part of achieving SDG2 targets; and 1310

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(iii) modeling such diversified agroecosystems using the 1311 smallest spatial unit adapted to represent the TES and 1312 the species spacing design. Finally, ESSU might be one 1313 component of the Duru et al.'s (2015) learning-support 1314 missing tools and knowledge gap about relations among 1315 practices, biodiversity, and associated ecosystem services. 1316 The ESSU concept could contribute to study and improve 1317 the performance of diversified agroecosystems in the tran-1318 sition to highly diversified agriculture. 1319

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