

Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge

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4	Facing up to the paradigm of ecological intensification in agronomy: revisiting methods,
5	concepts and knowledge
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24	comparative analysis
25	

26 Abstract

27 Agriculture is facing up to an increasing number of challenges, including the need to ensure 28 variousecosystem services and to resolve apparent conflicts betweenthem. One of the ways 29 forward for agriculture currently being debated is a set of principles grouped together under 30 the umbrella term "ecological intensification". In published studies, ecological intensification 31 has generally been considered to be based essentially on the use of biological regulation to 32 manage agroecosystems, at field, farm and landscape scales. We propose here five additional 33 avenues that agronomic research could follow to strengthen the ecological intensification of 34 current farming systems. We begin by assuming that progress in plant sciencesover the last 35 two decades provides new insight of potential use toagronomists. Potentially useful new 36 developments in plant science include advances in the fields of energy conversion by plants, 37 nitrogen use efficiency and defence mechanisms against pests. We then suggest that natural ecosystems may also provide sources of inspiration for cropping system design, in terms of 38 39 their structure and function on the onehand, and farmers' knowledge on the other. Natural 40 ecosystems display a number of interesting properties that could be incorporated into 41 agroecosystems. We discuss the value and limitations of attempting to 'mimic' their structure 42 and function, while considering the differences in objectives and constraints between these 43 two types of system. Farmers develop extensive knowledge of the systems they manage. We 44 discuss ways in which this knowledge could be combined with, or fed into scientific 45 knowledge and innovation, and the extent to which this is likely to be possible. The two remaining avenues concern methods. We suggest that agronomists make more use of meta-46 47 analysis and comparative system studies, these two types of methods being commonly used in 48 other disciplines but barely usedin agronomy. Meta-analysis would make it possible to 49 quantify variations of cropping system performances in interaction with soil and climate 50 conditions more accurately across environments and socio-economic contexts. Comparative

analysis would help to identify the structural characteristics of cropping and farming systems
underlying properties of interest. Such analysis can be performed with sets of performance
indicators and methods borrowed from ecology for analyses of the structure and organisation of
these systems. These five approaches should make it possible to deepen our knowledge of
agroecosystems for action.

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New agricultural systems are required toallow agriculture to satisfy the increasingly 62 63 diverse expectations of society. For decades, agronomy has produced knowledge and designed 64 agroecosystems for maximising the production of primary food and fibre, either for direct 65 consumption or for industrial use. Agricultural production issues have recently been expanded 66 toinclude other ecosystem services (Zhang et al., 2007). Likeother natural and semi-artificial 67 ecosystems, agroecosystems can provide services, such as carbon sequestration, pollination, or water filtration. The capacity of agriculture to provide such services is, of course, not 68 69 always guaranteed, and there are manyexamples of adverse effects of agricultural practiceson 70 the environment, leading to ecological disservices of agriculture (Matson et al., 1997; 71 Swinton et al., 2007). Disservices may include decreases in water and air quality or a 72 contribution to biodiversity loss. As agroecosystems are ecosystems controlled by humans, 73 adopting the correct approach to a wide range of production issues requires an understanding 74 of the way in which natural and human-driven or forced processes interact within the 75 ecosystem.

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Agronomists have argued that the missions of multi-objective agriculture could best be 77 78 achieved by making better use of biological regulation mechanisms at different levels: crop 79 management, cropping system design, landscape layout and management (Matson et al., 80 1997; Médiène et al., 2011). This assumes that biological mechanisms are able to replace 81 chemical or physical inputs, or to interact favourably with them, playing the same agronomic 82 role without external costs, including environmental costs in particular. The use of biological 83 regulation in agroecosystems to achieve both a high level of food production and to provide 84 ecosystem services, apparently opposite aims, has been placed at the core of what is 85 increasingly called "ecological intensification". The Food and Agriculture Organisation 86 (FAO, 2009)recently defined "ecological intensification" (or "sustainable intensification") 87 within the framework of organic agriculture as "Maximization of primary production per unit 88 area without compromising the ability of the system to sustain its productive capacity". The 89 expression"ecological intensification" was already in usemore than two decades ago (Egger, 90 1986), when it referred to a kind of ecological engineering in agropastoral systems in Africa, 91 replacing some perennial species to improve soil organic matter content.

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93 A more recent use of the expression by Cassman (1999) focused on cereal production and 94 highlighted the need for progress in plant and soil science to achieve a continuous increase in 95 cereal yields (intensification) without environmental (ecological) damage. This approach focuses principally on the fate of fertilisers and their use by crops. Witt et al. (2006) applied a 96 97 similar approach to oil palm plantations. According toChevassus-au-Louis and Griffon 98 (2008) and a number of other authors (Affholder et al., 2008; Mikolasec et al., 2009; Hubert et 99 al., 2010; Bommel et al., 2010), ecological intensification is a pathway towards the 100 production of more agricultural product, the production of "new" things (ecosystem services) 101 and different means of production (environmentally friendly). According to Chevassus-au-102 Louis and Griffon (2008), ecological intensification is basedon "intensification in the use of the natural functionalities that ecosystems offer". Though relatively vague, this definition 103 104 remains a possible starting point for the consideration of alternative pathways of development 105 foragriculture. This definition is much broader than that of Cassman (Cassman, 1999), and 106 provides an interestinghaven for scientists promoting the use of biological regulation in 107 agroecosystems.

109 Many articles have been published on biological regulation in agroecosystems, mostly under 110 the heading "agroecology", and new papers are continuing to appear. Research on this topic 111 remains highly necessary, and is probably a challenge for most agronomists familiar with 112 individualphysical and/or chemical aspects of agroecosystems. However, ecological 113 intensification calls for both a wider diversification of sources of knowledge and the 114 development of new data analysis methods. Agronomists have, until recently, relied 115 essentially on their own scientific output. Prototyping (e.g. Vereijken, 1997; Lancon et al., 116 2007; Debaeke et al., 2009) and the model-based design of agricultural systems (e.g. Rossing 117 et al., 1997; Bergez et al., 2010) are fed by results processed through simulation studies, 118 statistical hypothesis testing and group analysis, from research groups working mostly at 119 experimental stations(Figure 1). We argue here that agronomists would be placed in a better 120 position to tackle ecological intensification if they diversified their sources of knowledge and 121 the methods used to compile, organise and analyse such knowledge. The diversification of 122 knowledge sources may include (i) making use of recent advances in plant sciences, (ii) 123 learning lessons from the functioning of natural ecosystems, guiding the design and 124 management of acroecosystems and (iii) embracing local farmers' knowledge. Methods for 125 assessing these sources of knowledge are necessarily diverse, and couldbe extended to data 126 mining and the meta-analysis of large datasets containing heterogeneous information and 127 comparative analyses of agroecosystems at different scales. We present here the arguments 128 for further agronomic research in these two related domains: sources of knowledgefor 129 agronomists and data processing methods.

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131 **2.** Diversifying sources of knowledge to guide ecological intensification

132 **2.1 – Mobilizingadvances in plant sciences**

133 There has been tremendous progress in plant sciences in recent decades, with detailed 134 elucidation of the genetic and environmental determinism of plant development, growth and 135 reproduction. This progress was made possible, in particular, by increases in our ability 136 todissect cellular and molecular processes, supported by exponential progress in laboratory 137 techniques and the capacity to analyse masses of genomic data (e.g. Tardieu & Tuberosa, 138 2010). This knowledge about the highly complex life of plants has often been developed in a 139 simplified environment, far removed from the reality of farmers' fields. This has led to a 140 widening of the gap between the research objectives of plant scientists and agronomists.We 141 highlight briefly, with a few examples, ways in which agronomists could make use of 142 advances in plant sciencesto designecologically intensive cropping systems.

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144 <u>2.1.1.A new look at the basics</u>

145 Agronomists involved in the design and evaluation of cropping systems often make use of a 146 simplified crop description(Monteith 1977), despite the availability of more mechanistic 147 models simulating canopy photosynthesis (Spitters et al., 1986; Spitters 1986; Depury & 148 Farquhar, 1997). In this simplified description, the canopy, represented as a "big leaf", 149 intercepts photosynthetically active radiation and converts it to biomass. Branching is 150 generally considered to be the outcome of interplant competition. Mineral nutrition is 151 represented as a simple flux from soil to plant roots, depending on soil mineral and water 152 contents. Such simplified representations have proved sufficient and highly successful for cropping system design. Moreover, the more sophisticated representations of the basic 153 154 processes of plant life implemented in more complex models do not necessarily improve he 155 ability of crop models to predict behaviour in a range of fluctuating conditions. Such 156 representations have therefore been used only rarely by agronomists. Nevertheless, results 157 recently obtained in plant sciences suggest that this simple paradigm could be improved, as

shown for example by Zhu *et al.* (2010), who analysed the ways in which improvements in
photosynthesis efficiency could contribute to the required increase in yields.

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161 Nutrient use efficiency is alsoclearly a keypoint in ecological intensification. One of the most 162 important issues is decreasing the use of nitrogen fertilisers, to decrease greenhouse gas 163 emissions, to reduce the dependence of agriculture on fossil fuels and to prevent health and 164 environmental disorders, without decreasing productivity (Galloway et al., 2008; Spiertz, 165 2010). Plant scientists have investigated in detail the exchanges of nitrogen between roots and 166 their environment (Jackson et al., 2008). Glass (2003) summarised the factors decreasing 167 nitrogen absorption efficiency, on the basis of molecular knowledge and empirical data. 168 Decreases in nitrogen transporter activity and rates of nitrate absorption follow increases in 169 soil ammonium concentration, low temperature and incident radiation. These mechanisms may account, at least in part, for the high variability of fertiliser efficiency observed in field 170 171 experiments. They also provide us with opportunities to improve nitrogen management in the 172 soil. More generally, the ways in which plants make use of adaptation mechanisms to deal 173 with mineral depletion have been extensively studied on a physiological basis (Grossman & 174 Takahashi, 2001). Agronomists could make use of this work to define the limits within which 175 plant environments must be contained to avoid unfavourable plant reactions.

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177 <u>2.1.2. The cultivated plant and its biological environment</u>

Since the middle of the last century, the gradual "artificialisation" of agriculture has led to agronomists paying less attention to the biological components of fields. Agroecology has emerged as a reaction against this excessive simplification of the system, placing the biological component back at the heart of the system (Altieri, 1989), and resulting in the development of an"agroecosystem"view (Conway, 1987). Nevertheless, common agronomic practices still largely ignore biological interactions in cultivated fields, and agroecologists often emphasise the need for an empirical and holistic approach to agroecosystems. New findings in plant sciences concerning the relationships between the plant and its surrounding biotic environment have recently emerged and are of great interest.

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188 Studies of interactions between roots and soil micro-and macro-organisms have revealed the 189 existence of processes of paramount importance for agronomists. Some of these interactions 190 are very familiar to agronomists, including nitrogen fixation by symbiosis between Rhizobium 191 sp.and leguminous or non-leguminous(Mehboob et al., 2009) plants. Other associations, such 192 as that between other endophytic di-azotrophic bacteria and grasses or cereals, also exist and 193 may be of interest, as pointed out by Reis et al. (2000). Plants may be injured by soil 194 pathogenic organisms, but they may also benefit from organisms present in the rhizosphere, 195 through improvements in growth and mineral nutrition, an increase in resistance to 196 unfavourable abiotic conditions, and protection against or an increase in resistance to 197 pathogens (Sturz & Nowak, 2000; Kiers and Denison, 2008).

198

199 Whatever the types of organisms considered, the species or plant genotype drives selection of 200 the bacterial community and determines the benefits of plant-rhizosphere mutualism. 201 Improvements in the genomic characterisation of rhizobacterial communities have made it 202 possible to demonstrate that plant genotype influences bacterial assemblages by modifying 203 exudation patterns (Micallef et al., 2009). An understanding of the plant genome would make 204 it possible to determine the genetic basis of the mechanism and to make use of genetic 205 variants for the management and manipulation of the rhizosphere community (Ryan et al., 206 2009; Wissuwa et al., 2009). These rhizosphere associations and their benefits to the crop also 207 depend strongly on cropping system, so it would seem reasonable to conclude that adapted 208 cropping systems (including crop rotation and crop management measures) could also 209 increase efficiency. The efficacy of the Rhizobium/legume association is also highly 210 dependent on cropping system, through the effects of practices on the physical and chemical 211 properties of soils and their water status (Sprent et al., 1987). These effects are well known, 212 but should be considered in the light of the recent development of legume nodulation 213 genomics (Stacey et al., 2006). Sturz and Nowak (2000) have enlarged their vision to the 214 overall communities of endophytic rhizobacteria with potentially beneficial effects on crop 215 growth through an increase in resistance to unfavourable abiotic conditions and to pathogen 216 aggression, and through improvements in growth and mineral nutrition. The agronomic benefits of these associations with endophytic rhizobacteria depend on the survival of 217 218 bacterial communities, which in turn depends on soil and crop management (Bowen and 219 Rovira, 1999; Acosta-Martinez et al., 2008). One of the ways by which crop management can 220 modulate the evolution of microbial communities, is its effect on root exudates. In addition to 221 altering the physical and chemical properties of the soil, root exudates have been shown to 222 affect both soil micro-organism communities and other eukaryotes (Bertin et al., 2003). Bais 223 et al. (2004, 2006) reviewed the nature of the chemicals involved and the corresponding 224 interaction processes for various ecological roles. However, one of the aspects of crop/soil 225 community interactions most frequently ignored by agronomists is probably the role of the 226 common mycorrhizal networks (CMNs), which may be affected directly or indirectly by soil 227 tillage, fertilisers, pesticide use and aerial plant management (Pietikainen & Kytoviita, 2007). The networks that these fungi establish between plants may provide a major route for mineral 228 229 transfer from plant to plant (He et al. 2003). Van der Heijden and Horton (2009) recently 230 reviewed the possibilities for CMN formation between different plant species, their ecological 231 significance and the benefits generated. They found that there were many possibilities for CMN development, but that there were also large differences in the benefits accrued, 232

233 particularly in terms of promotion of the growth of interconnected plants. Similarly, the role 234 of plant micro-organisms in plant x plant interactions (Sanon et al., 2009; Li et al., 2008) and 235 the competition of microbial communities promoting both plant growth and health 236 (Lemanceau et al., 2009) illustrate the benefits that agronomists may obtain from advances in 237 research on plant-micro-organism interactions for rhizosphere engineering and management 238 (Ryan et al., 2009). Beyond the question of production, Jackson et al. (2008), focusing on 239 nitrogen, derived from current knowledge on root/micro-organism interactions the trends in 240 ecosystem services supplied by cropping systems in different agricultural situations. Thanks 241 to the deep insight now available, the contribution of agronomists at system level can be built 242 on mechanistic rather than empirical knowledge, as demonstrated by certain examples in 243 precision agriculture(Welbaum et al., 2004).

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245 Interactions between aerial parts of the plant and the surrounding biotic environment have 246 also been described in detail in recent years. The metabolic pathways bywhich plants react 247 both locally and systemically to infection or wounding are increasingly well known (De Bruxelles & Roberts, 2001; Kessler & Baldwin, 2002). Some result in the production of 248 249 volatile substances, which play a role in herbivore repulsion or plant-to-plant signalling. 250 These findings are promising for genetic engineering approaches, provided that the genetic 251 basis of the metabolic pathways can be identified (Dudareva & Pichersky, 2008). 252 However, cropping system may also play a role, as the expression of the metabolic pathways 253 involved in direct or indirect defence probably depends on interactions between genotype and 254 environment (Le Bot et al., 2009). Moreover, it may be possible to elicit some of these 255 pathways deliberately, with appropriate techniques.

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257 <u>2.1.3. Ways to improve the use of plant sciences for ecological intensification</u>

258 The preceding two sections do not provide a detailed review of the extensive literature in 259 plant sciences. Instead, they deal with a few examples of recent progress and the possible 260 benefits that agronomists could derive from these advances (see table 1). These examples 261 demonstrate that closer consideration of the results of plant sciences could help agronomists 262 to reach their objectives, paving the way for higher levels of production, better quality 263 products, and less harmful consequences for the environment. Other advances in plant 264 sciences, concerningplant architecture, leaf and root morphogenesis (McSteen & Leyser, 265 2005; Wang & Li, 2008; Walter et al., 2009), floral biology (e.g. Boss et al., 2004), the role of 266 aquaporins (e.g. Maurel et al., 2008), cell separation processes (Roberts et al., 2002) and long 267 distance signals within plants (Lough & Lucas, 2006), for example, are also of great potential 268 interest to agronomists working on ecological intensification, as they might help crops to avoid 269 or to resist deleterious stresses. However, major efforts are still required to scale-up the results 270 from individual genes, cells or organs to the canopy, and to test the stability of biological 271 results in a wide range of agricultural conditions. It is also important to check that advances in 272 one area are not associated with severe drawbacks in others. However, these findings are 273 nonetheless precious to agronomists, who will need to use all the means available to construct 274 novel, more resource-use efficient and/or productivecropping systems.

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Finally, there are many different drivers of change in ecological intensification (see introduction and subsequent sections). Innovative systems that have already been developed in the domain of ecological intensification, such as the use of mixtures of cultivars or species, agroforestry andno-tillage systems, would certainly benefit from the knowledge provided by plant sciences. However, these systems will themselves raise new questions and issue new challenges to plant science. For example, although progress has been made in this area, plant sciences results are still often obtained in highlysimplified systems and therefore cannot easily be translated to multispecies systems. Above-ground competition for light and below-ground
competition for water are major processes inecological intensification that require study in
systems including facilitation between plants (Long & Nair, 1999;Zhang *et al.*, 2008;
Malézieux *et al.*, 2009).

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288 **2.2** - Learninglessons from the functioning of natural ecosystems

289 Strategies for agroecosystem design and management may be derived from the observation of 290 natural ecosystems, guiding alternative agronomic practices (Malézieux, 2011). Several 291 authors (e.g. Ewel, 1999; Altieri, 2002; Jackson, 2002; Vandermeer, 2003) have already 292 suggested that natural ecosystems may provide appropriate models for agroecosystem design 293 to achieve both environmental and social goals while ensuring long-term sustainability. This 294 idea is based on the assumption that natural ecosystems are adapted to local constraints, due to 295 a long process of natural selection (Dawson & Fry, 1998; Ewel, 1999). It is therefore assumed 296 that the incorporation of certain characteristics of natural ecosystems into agroecosystems 297 would improve some of the properties of agroecosystems, such as productivity (Fukai, 1993), 298 stability (Aerts, 1999; Schulte et al., 2002) and resilience (Lefroy et al., 1999). These features 299 are particularly useful for dealing with pest outbreaks (Trenbath, 1993) and increasing energy 300 efficiency in a context of the depletion of fossil fuels (Hatfield, 1997). A similar reasoning was followed in the framework of Ecoagriculture, proposed by McNeely andScherr (2003), 301 302 which places biodiversity at the heart of strategies to conserve and restore ecosystem services, 303 increase wild populations in agroecosystems, and sustain agricultural production. An 304 illustration of this mimicry is provided for cropping systems in Figure 2 with an emphasis on 305 crop protection. In natural ecosystems, the various animal and plant species interact through 306 population dynamics and trophic networks, providing the final ecosystem with services, such 307 as pollination. In standard cropping systems, these interactions may lead to pest damage on 308 crops, which may be managed with various control methods to limit yield loss. An increase in
309 plant species diversity in systems mimicking natural ecosystems could allow natural enemies
310 to control pests and generate ecosystem services.

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- 312
- 313 <u>2.2.1 What does "Mimicking natural ecosystems" mean?</u>

314 There have been only a few practical attempts to design agroecosystems from nature. Jackson 315 and Jackson (1999) aimed to develop sustainable cropping systems by mimicking the mid-316 grass American prairie, creating crop mixtures analogous to the vegetationstructure of the 317 prairie. Traditional agroecosystems in the tropics, long unknown or disparaged by some 318 agronomists, are frequently based on the integrated management of local natural resources 319 and, in many cases, on the management of local biodiversity. These systems may also be 320 considered to result from the observation of nearby natural ecosystems by generations of 321 farmers, who have aimed to mimic the functioning and structure of these natural systems. For 322 example, slash and burn systems can be considered to mimic nature behaviour after fire. 323 Agroforestry systems in the humid tropics mimic the structure and functioning of rainforests. 324 According to Ewel (1999), humid tropical ecosystems appear to be particularly suitable for 325 application of the "mimicry of Nature" concept. Agroforestry systems in the humid tropics are 326 based on the tropical rainforest model. They combine several strata, have a high level of 327 species diversity and are very widespread in Asia, Oceania, Africa and Latin America. Such 328 systemsprovideboth subsistence for local populations and major environmental and socio-329 economic services (Sanchez, 1995; Nair, 2001). Lying halfway between agro- and forest 330 ecosystems, agroforestry systems combine annual and perennial, herbaceous and woody 331 species, in a more or less complex whole in terms of the number of plant species and practices 332 (Torquebiau, 2007). The damar agroforests of Sumatra, or the cocoa-based agroforests of Cameroon or Costa Rica, are original ways in which farming communities use natural resources in human reconstructions of both "natural" and productive ecosystems from natural ecosystems (Michon *et al.*, 1995, 2007; Schroth *et al.*, 2001, 2004).

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337 The scientific foundations of the mimicry paradigm, however, remain to be studied 338 thoroughly (Malézieux, 2011). The potential of this approach to generate innovative 339 agroecosystems in practice also remains largely unknown. Ewel (1999) and Van Noordwijck 340 and Ong (1999) proposed two principles for the design of agroecosystems based onnatural 341 ecosystem mimicry. According to the first of these principles, agroecosystems should mimic 342 the structure and function of natural ecosystems existing in a given pedoclimatic zone. 343 According to the second, agroecosystems should also mimic the diversity of species existing 344 in natural ecosystems, thereby maintaining the diversity of natural ecosystems in the given 345 zone. The first of these principles is clear enough, but must be extended to be effective. 346 Indeed, there are many functions, and structure can be assessed at different scales. 347 Furthermore, basing agroecosytem design solely on natural ecosystems present in the same 348 area may be too limiting: some good ideas might emerge from the study of very distant 349 systems.

350

According to the second principle, the redesign of agroecosystems inmore ecologically intensive configurations implies their diversification. This has been the case, for example, in Cuba, where small- and medium-scale farmers have tended to diversify their production systems in response to their limited access to or total lack of agricultural inputs to sustain productivity (Funez-Monzote *et al.*, 2009).The resulting diversified systems areenergetically more efficient, less dependent on external inputs, more productive, adaptable and resilient. The diversification of agroecosystems within the mimicry paradigm may be achieved by 358 increasing the number of microorganisms, plant and animal species relevant to agriculture 359 overspace and time, or through agrobiodiversity, a subset of general biodiversity (Brookfield 360 et al., 2003). However, natural ecosystem mimicry cannot mean reproducing the diversity 361 observed in natural ecosystems, for at least three reasons. First, recent reviews of existing 362 knowledge in ecology have demonstrated that functional composition controls ecosystem 363 functioning more frequently than species diversity (Hooper et al., 2005). As our purpose is to 364 improve agroecosystem functioning through ecological intensification, and not to conserve 365 natural species biodiversity per se within agroecosystems, agronomists should concentrate on 366 identification of the level of functional biodiversity resulting in the expression of interesting 367 properties. As pointed outby Main (1999), who addressed the question of how much 368 biodiversity is enough in the context of agroecosystems mimicking nature, the level of 369 diversity considered adequate strongly depends on the goals and criteria used forevaluation. 370 Moreover, interesting properties may arise from the spatial and temporal organisation of the 371 species rather than purely from their number. For example, lessons can be learned from studies 372 of natural ecosystems addressing agronomic topics: nutrient cycling within a complex 373 landscapemay be useful for optimising nutrient management in areas worked by humans, 374 community ecology in natural ecosystems may facilitate the design of new crop protection 375 strategies and an understanding of facilitation within natural ecosystems should make it easier 376 to make use of this process in agroecosystems. Finally, approaches based on mimicking 377 natural ecosystems will inevitably be confronted with the "aim problem". Natural ecosystems 378 provide many services but are not targeted. Agroecosystems, by contrast, are designed to 379 optimise different aspects and toachieve different goals. Consequently approaches mimicking 380 natural ecosystems are limited by certainagricultural obligations, such as the removal of the 381 minerals contained in agricultural products. Some insight may be gained from regarding

382 agroecosystems as complex systems with many simultaneous feedback loops including a383 dimension absent from natural ecosystems: human agency.

384

385 <u>2.2.2 Agroecosystems as complex socio-ecological systems</u>

386 Agroecosystems are systems that combine sociological and ecological dynamics, in 387 interaction. In complex, dynamic and spatially heterogeneous systems, interactions take place 388 over scales generating emergent properties and self-regulatory mechanisms (Holling, 1973). 389 These mechanisms often manifest as cross-scale feedback, or panarchy (Gunderson et al., 390 2002), and societies contribute to system regulation through adaptive management. For 391 example, in smallholder agricultural systems making use of communally shared resources, 392 buffering and regulatory mechanisms often emerge from collective action (Meinzen-Dick et al., 2004). This is why agroecosystems may be defined as socio-ecological systems, or 393 394 cybernetic systems steered by humans to attain certain goals (see Conway, 1987). The 395 capacity of farmers to adapt plays a major role in system resilience and, by analogy to the 396 concept of informal economies (de Soto, 2000), regulatory mechanisms operate as informal 397 resource flows that are often unaccounted for in agroecosystems analysis (Tittonell et al., 398 2009). Just as natural ecosystems have a"memory" as a direct consequence of their history, so 399 do agroecosystems, except that some of that memory lies in human agency (Tittonell, 2007).

400

401 A wider definition of agroecosystem diversification, more compatible with the socio-402 ecological nature of complex agroecosystems, must consider not only species diversity, but 403 also the diversity of agricultural practices and rural knowledge adapted to/derived from local 404 pedoclimatic conditions. These lie at the core of human agency and represent new sources of 405 knowledge for agronomic research (see below). Agroecosystem diversification in its 406 broadestsense thus concerns the diversity of livelihood strategies ata certain location, diverse 407 land use, management and marketing strategies, the integration of production activities (e.g. 408 crop-livestock interactions), spatial and temporal associations of crops and crop cultivars, and 409 the maintenance of genetic agrobiodiversity in the system. The efficiency of use of natural, 410 economic and social resources in agroecosystems ---which goes beyond the partial use 411 efficiency of a certain single input ---and desirable properties, such as stability and 412 resilience, are based on one or more of these categories of diversity. New avenues for 413 agronomy to strengthen agroecological intensification should go beyond the cultivated field or 414 the mixture of species in a given landscape. They should explore desirable properties and 415 mechanisms that operate at the scale of complex socio-ecological systems *i.e.* that take into 416 account sociological and ecological dynamics and interactions in agroecosystems.

417

418 2.3 - Farmers' knowledge and lay expertisevalorisation and integration into scientific 419 knowledge

420 Farmers do not rely exclusively on the results and output of agronomic research to operate 421 their agroecosystems. They make use of much wider knowledge, based on their own 422 experiences and on exchanges with other farmers and advisers, thus building their own 423 expertise. This expertise is rooted in the need to act whatever the level of agronomic 424 knowledge available: sound and detailed or unreliable and patchy. It is also dependent on the 425 characteristics (environmental, economic, social) of the situation in which it is constructed. 426 According toPrior (2003), we may consider farmers to belay experts (although this 427 denomination entails an antinomy): experts because of their experience-basedknowledge 428 andlay because this knowledge is limited in scope and doesnot give farmersthe broader and 429 deductive understanding characteristic of scientific or expert knowledge. Recognition of the 430 value of lay expertise is both a necessity and a challenge in many domains, such as medicine 431 (e.g. adapting treatments according to the patient's reactions, both as observed by doctors and as interpreted by the patient) and industry (particularlyfor fault detection in plant or machine
operation). However, although the value of this lay expertise is recognized, it is not used to
build or extend the current scientific knowledge, but to adapt its application in local situations
(Henderson, 2010).

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437 Farmers can observe not only their own production systems, but also other systems (both 438 agricultural and natural) and interactions between these systems. They can also 439 gainexperimental knowledge in their own systems. They are often willing to do so and 440 therefore carry out experiments in the operation of their own agroecosystem, evaluating the 441 response of the system to their decisions. This generates different types of knowledge. When 442 confronted with, observing or learning from natural ecosystems, farmers gain knowledge 443 similar to what is generally referred to as *local* or *traditional ecological knowledge* (LEK or 444 TEK, Berkes, 1999). Over generations, they may also build traditional knowledge (not 445 specifically ecological), refined by years of adaptation (see previous section). When 446 experimenting, they build a mixture of experience-based and experimental knowledge. Many 447 studies have considered the use of LEK/TEK, but most have focused on the use of this 448 knowledge for natural resource management (including fisheries and forestry systems, which 449 more closely resemble a subsistence harvesting activity) rather than the design or 450 improvement of productive agricultural systems. Fewer studies have directly investigated 451 farmers' knowledge. The studies that have been carried out in this domain have mostly 452 assessed the validity of this knowledge (e.g.Grossman, 2003; Friedman et al., 2007; Grace et 453 al, 2009) or considered the local adaptation of more generic solutions (e.g. Steiner, 1998, 454 Affholder et al., 2010). However, farmers' knowledge is not only of value for application and 455 for the adaptation of agronomic knowledge to a particular case. It can also be used to extend the available scientific agronomic knowledge (see the examples presented in Table 2). Wewill defend this point and discuss the various issues it raises below.

458

459 <u>2.3.1. Value of farmers' knowledge for agronomy</u>

460 We will analyse separately the lay expertise (resulting from farmers' activities and 461 interactions with their own systems) and the more traditional knowledge that some farmers or 462 societies have developedover time. The value of lay expertise for agronomy and for 463 development (support to farmers) has been recognised for some time (e.g. Barzman et al., 464 1996; Baars & de Vries, 1999). This lay expertise can helpto enlargecurrent agronomic 465 knowledge in variousways. First, farmers operate their agroecosystem even in the absence of 466 appropriate knowledge, because they have to. They therefore develop experience-based 467 knowledge that can fill in some of the gaps in scientific knowledge. However, as mentioned 468 above, this experience-based knowledge is often limited to the farmer's own particular case, 469 whereas scientific knowledge should be more general.

470

471 Second, some traditional practices are based on the observation of natural ecosystems 472 (Chalmers & Fabricius, 2007; Reed et al., 2007), which, as we have seen, may be of value 473 forecological intensification. Chalmers & Fabricius (2007), for example, showed that local 474 experts, using their ecological knowledge, were able to put forward explanations for changes 475 intheir system, some of which were also provided by scientific knowledge. However, the local 476 experts also had other explanations rooted in a more generalunderstanding of the system. 477 Traditional farming systems can also be a source of understanding and inspiration for the 478 design of sustainable farming systems. Singh & Sureja (2008) showed, for example, how 479 traditional farming systems cope with harsh environments through the management of a wide 480 diversity of plants providing genetic resources. Abbona et al. (2007) evaluated the 481 sustainability of a traditional vineyard system in Argentina, both in its original location and in 482 a newly planted area. They showed that the traditional system, in its original location, 483 wasindeed sustainable, whereas this system was not sustainable in its new, different location. 484 They concluded that the efficacy of the traditional system was dependent on the location in 485 which and for which it had been developed over time. During this evaluation process, based 486 on the use of indicators developed for this analysis through the adaptation of existing 487 methods, these authors gained insight into and an understanding of the ecological processes at 488 work in the traditional vineyard system. The analysis of traditional farmers' practices 489 therefore provided an opportunity to obtain new scientific knowledge. In a different context, 490 Ballard et al. (2008) analysed the knowledge involved in the management and monitoring 491 activities of community-based forestry groups and the ways in which local and scientific 492 knowledge complemented each other. They showed that local knowledge provided a rapid and efficient means of assessing the effects of management practices on the forest. The same 493 494 was found forgreenhouse tomatomanagement. Tchamitchian et al. (2006) successfully used 495 the concept of "crop vigour" as an indicator in their expert system controlling the daily 496 greenhouse climate for tomato production. Tomato cropvigour is readily assessed by growers 497 of greenhouse tomato crops, on the basis of a set of observations: plant tip colour and shape, 498 fruit load on the crop, crop overall colour. Scientists relate these observations to the 499 generative to vegetative balance of the crop ability and its to perform 500 photosynthesis(Navarrete et al. 1997), without being able to model it formally.

501

Taken as a whole, local knowledge and lay expertise can provide clues to the natural or ecological processes most useful in the design of sustainable farming systems, such as the natural regulation of pest populations by their predators (Barzman *et al.*, 1996; Sinzogan *et al.* 2004), or management of the soil and its mineral balance (Steiner, 1998; Okoba & de Graaf, 2005; Saito *et al.*, 2006; Abbona *et al.*, 2007). They can also be of value in the design of
assessment methods or indicators for monitoring the ecological performances of these farming
systems.

509

510 2.3.2 Qualification and validation of lay expertise and knowledge expression

511 Although both interesting and challenging, the lay expertise of farmers (or advisers) is not 512 easy to use. First, this lay expertise must be elicited and represented. Several methodologies 513 have been proposed for expert knowledge elicitation, either for specific applications, such as 514 plant disease epidemics (Hughes & Madden, 2002), or for more general applications 515 (Cornelissen et al., 2003; Ley et al., 2010). Appropriate elicitation methods include the 516 selection of apanel of experts and the associated delimitation of the knowledge domain 517 considered. The choice of representation also influences the elicitation process. Many authors 518 advocate the use of fuzzy models, which allow the use of linguistic terms and are more 519 suitable for the expression of knowledge in qualitative rather than quantitative terms. By 520 contrast, scientific knowledge is most frequently modelled in quantitative terms, 521 particularlywhen the goal is to represent the operation of a system under the influence of both 522 controlled (human decisions and actions) and uncontrolled (environment) factors. Most of the 523 agronomic models built to simulate agroecosystems are numerical models in which 524 thevariables have point values rather than interval or probabilistic values. There is therefore a 525 gap between the most common representation of scientific knowledge and that of lay 526 expertise, hindering the combination and merging of these two types of knowledge. However, 527 differences in representation are not the only difficulty. As pointed outby Prior (2003), lay 528 experts maybe wrong, either because of the limited scope of their experience or because their 529 conclusions are based on false premises (misobservations, for example, due to a lack of 530 knowledge or skills). Their knowledge is also situation-dependent in that it is obtained in a

531 domain of low variability (one of the goals of agricultural practices is often to reduce 532 variability and diversity in agroecosystems, a goal challenged by ecological intensification). 533 Lay expertise should therefore be qualified and analysed independently, in several different 534 ways: domain of validity, certainty and precision. The domain of validity is important because 535 knowledge should be associated with a description of the domain in which it was obtained 536 (rangesof the variables considered, for example); this factor can be used to analyse the extent 537 to which the knowledge obtained is generic. Certainty refers to the confidence that can be 538 attributed to the knowledge. Finally, precision measures how close to a numerical expression it 539 is possible to get in the expression of the knowledge. Even certain knowledge may display a 540 low precision rendering its use purely hypothetical (ventilating a greenhouse does modify its 541 temperature, but the change is difficult to indicate with precision). Artificial intelligence 542 provides a framework for representing expertise and analysing the conflicts arising when 543 information from different sources is compared (several lay experts or a combination of lay 544 expertise and scientific knowledge; Amgoud & Kaci, 2007; Bench-Capon & Dunne, 2007; 545 Alsinet et al. 2008; Amgoud & Prade, 2009). However, this domain (qualitative reasoning and 546 argumentation) is still developing and, to our knowledge, its concepts and tools have not yet 547 been used to merge lay expertise and scientific knowledge in agronomy (there are applications 548 for database fusion, assisting debate preparation and industrial planning). The added value of 549 these approaches lies in the need to provide an explanation detailing the arguments supporting 550 a piece of knowledge, therefore addressing the questions of certainty and precisionraised 551 above.

552

553 The qualification of lay expertise has been shown to be a necessary step in approaches aiming 554 to combine this expertise with scientific knowledge. Going beyond the issues of the domain of 555 validity, certainty and precision, there is the question of validation of the new knowledge 556 obtained. However, classical validation procedures cannot readily be applied, because the 557 observations underlying the experience-based knowledge acquired are lacking. For example, 558 to validate the greenhouse management rules formalised from expert knowledge, 559 Tchamitchian *et al.* (2006) used a two-step method rather than a direct validation of the rules 560 themselves, which was not possible. The first step involved checking that the application of 561 these rules really did result in the desired pattern of behaviour in the greenhouse (as expressed 562 when building the rules), without questioning the agronomic validity of this behaviour. The 563 second step involved assessing the quality of production obtained by applying these rules, the 564 goal being to obtain appropriate production levels from the greenhouse. Attempts at the direct 565 validation of a given rule have only made explicit which pieces of agronomic knowledge can 566 be used to support a given rule. However, it would not have been possible to design the rule 567 from this identified scientific knowledge, generally because the scopes of the scientific knowledge and that of the lay expertise yielding the rule were different. 568

569

570 **3. Methods for synthesizing information**

571 The three main research methods currently used by agronomists (figure 1) are various types of 572 field experiments, on-farm inquiries (e.g. Doré et al., 2008), and modelling (e.g. Rossing et 573 al., 1997; Bergez et al., 2010). Field experiments provide validated knowledge meeting the 574 scientific rules for data acquisition. This basic knowledge can be supplemented by inquiries 575 providing data from real-world agricultural situations (farms). Modelling can be used to 576 explore the response of key agronomic and environmental variables, such as, for 577 example, yield or nitrogen loss, to climate, cropping system variables or societal changes. 578 Thedata generated are then processed, mostly by classical methods, such as simulation studies, single-experiment data analysis, or group analysis. These methods could probably be 579 580 complemented with two other methods: meta-analysis, involving the statistical synthesis of results from a series of studies, and comparative analyses of agroecosystems, involving the use of large-scale comparisons similar to those used in ecology (*e.g.* Fortunel *et al.*, 2009).

583

584 **3.1. Meta-analysis and agronomy**

585 Meta-analysis (e.g., Borenstein *et al.*, 2009)is more powerful than a simple narrative review 586 of a series of studies, because it synthesises published data in a quantitative manner and 587 makes it possible to assess thebetween-study variability of a variable of interest.

588

Both scientific researchers and decision-makers can benefit from meta-analysis in several ways (Sutton *et al.*, 2000), as this approachprovides a methodological framework for (i) exploringwhat has already been done on a given research topic and identifying more clearly where the gaps and uncertaintieslie,(ii)generating an overview ofdivergent results, (iii) guidingdecisions based on a systematic review and statistical analysis of all the available data related to a given topic, (iv) broadening the knowledge base and allowing replication for the testing of hypotheses, (v) adding to the cumulative development of science.

596

597 Most meta-analyses carried out to date have been performed in medical science (Normand, 598 1999; Sutton et al., 2000). This approach has been less systematically applied in other areas of 599 research, such as ecology (e.g., Arnqvist & Wooster, 1995; Cardinaleet al., 2006), and has 600 sometimes been applied inagriculture (e.g. Bengtsson et al., 2005), animal science (Sauvant et 601 al. 2008) and plant pathology (Rosenberg et al., 2004). In agronomy, meta-analysis methods 602 have generally been used to compare the effects of different cropping techniques or of 603 different cropping systems on yield or biomass production. For example, Miguez & Bollero 604 (2005) used a meta-analysis method to summarise and describequantitatively the effect of 605 several winter cover crops on maize yield. The authors estimated the ratio of maize yield after

606 a winter cover crop to maize yield with no cover from 37 published studies carried out in 607 various regions of the USA and Canada. In another study, Miguez et al. (2008) studied the 608 effects of planting density and nitrogen fertiliser on the biomass production of *Miscanthus x* 609 giganteus, using 31 published studies including biomass measurements at different dates 610 overseveral years. Drawing on published studies on sub-Saharan African agriculture, 611 Chikowo et al. (2010) conducted a meta-analysis of factors controlling nitrogen and 612 phosphorus capture and conversion efficiencies by major cereal crops. The meta-analysis 613 carried out by Badgley et al. (2007) did not focus on a specific cropping technique, but was 614 performed to compare two agricultural systems: organic versus conventional or low-intensity. 615 The authors compared the yields obtained in an organic system with those obtained in 616 conventional or low-intensity food production systems, based on yield data from 293 617 individual studies on various crops. These data were used to estimate the meanyield ratio for 618 variousfood categories, for both developed and developing countries.

619

Diverse techniques for meta-analysis are available (e.g., Borenstein *et al.* 2009; Sutton *et al.*,
2000), but meta-analysis should always include the following steps:

- i. Definition of the objective of the meta-analysis and of the variable of interest
 to be estimated from the data (e.g., in Miguez and Bollero 2005, the variable of
 interest is the ratio of maize yield after a winter cover crop to maize yield in
 the absence of a cover crop).
- 626 ii. Systematic review of the literature and/or of the dataset reporting values of the627 quantities of interest.
- 628 iii. Analysis of data quality (i.e., quality of the experimental designs and of the629 measurement techniques).

Assessment of between-study variability and heterogeneity. Evaluation of the 630 iv. 631 between-study variability of the variable of interest and of the heterogeneity of 632 the accuracy of individual estimates is an important step in a meta-analysis and 633 several statistical methods have been proposed to estimate between- and 634 within-study variances (Borenstein et al., 2009). Combination of the individual 635 study estimates and estimation of a mean value for the variable of interest, for example, can be achieved by calculating a weighted sum of individual 636 637 estimates derived from the studies collected in step ii.

v. Assessment of publication bias. Publication bias occurs when only studies with
highly significant results are published. In this case, a meta-analysis can lead to
a biased conclusion and overestimation of the effect of a given factor. The
'funnel plot' technique can be used to deal with this issue (e.g., Borenstein *et al.*, 2009).

643 vi. Presentation of the results and of the level of uncertainty.

644

In the context of ecological intensification, the meta-analysis framework constitutes an 645 646 interesting alternative to dynamic crop models. Dynamic crop models can be used both to 647 assess the consequences of cropping techniques and environmental variables forcrop 648 production (e.g., Jones & Thornton, 2003) and to assess the effect of cropping systems on keyenvironmental variables (e.g., Rolland et al., 2008), two key issues for ecological 649 650 intensification. However, these models include several sources of uncertainty (Monod et al., 651 2006) and their predictions are not always reliable (e.g., Barbottin et al., 2008; Makowski et 652 al., 2009). We believe that meta-analysis should be more systematically used by agronomists, 653 to assess and compare the effects of cropping systems on productivity, risks of soil and water 654 pollution, greenhouse gas emissions and biodiversity. A considerable body of experimental

data is available for such purposes (e.g., Rochette & Janzen, 2005). Such data could be reviewed, combinedand analysed withstatistical techniques, to rank cropping systems as a function of their impact on key environmental variables, such as water nitrate content, greenhouse gas emissions (e.g., N_2O) and the presence/absence of species of ecological interest (e.g., earthworms, birds). However, meta-analysis requires the use of appropriate techniques and the value of a meta-analysis may be greatly decreased if the six steps outlined above are not rigorously implemented.

662

663 **3.2. Comparative analysis of agroecosystems**

664 Informationuseful for the ecological intensification of agroecosystems may be obtained from 665 comparative analyses of the structural and functional properties and performance of 666 contrasting agroecosystems. Similar approaches, based on temporal or spatial comparisons, 667 are used in other fields of research, such as plant sciences (Wright et al., 2004; Vile et al., 668 2005; Mauseth, 2006), evolution sciences (Schluessel et al., 2008) and marine ecology 669 (Fuhrman & Steele, 2008). The comparative analysis of agroecosystems and comparisons of 670 agroecosystems with natural ecosystems involve the simultaneous analysis of multiple 671 criteria, with evaluation of the extent to which they displayspecific system properties. Several 672 approaches have been proposed for this purpose (e.g., Pannel and Glenn, 2000; de Bie, 2000; 673 Xu and Mage, 2001; Lopez-Ridaura et al., 2002; Giampietro, 2003), based largely on 674 concepts formulated more than a decade ago, by authors such as Conway (1987) andMartern 675 (1988). These methods evaluate indicators relating to the properties of agroecosystems, such as 676 productivity, stability and resilience. These properties are often interdependent and, as pointed 677 out by Marten (1988), they are not universal and must be redefined under each new set of 678 conditions. As discussed above, studies of the local knowledge sustaining various 679 mechanisms of indigenous resilience across contrasting agroecosystems, particularly at the

scale of the landscape and its functionality (e.g., Birman *et al.*, 2010), are also a promising starting point for obtaining information useful for ecological intensification. In the next few paragraphs, we examine briefly some critical issues relating to the choice of indicators in multicriteria evaluations (3.2.1) and identify innovative ways of looking at the relationship between structure and function in agroecosystems.

686 <u>3.2.1 Comparative analysis based on multiple indicators</u>

687 In practice, the implementation of multicriteria analytical frameworks often involves the 688 selection of a number of indicators (or the use of a list of predetermined indicators) and of 689 reference threshold values for each indicator. The selection of indicators is frequently biased 690 towards the disciplinary standpoint of the observer or highly influenced by certain stakeholders, so 'quality control' methods for evaluating the choice of indicators are 691 692 necessary. In their examination of the choice of indicators in different case studies, Groot and 693 Pacini (2010) argued that multicriteria evaluations should involve the analysis of four main 694 system properties: performance, diversity, coherence and connectedness, which can be 695 approached from four dimensions: physical, ecological, productive and social. Performance 696 relates to functional properties of the agroecosystem, such as capacity, stability and resilience. 697 Diversity relates to the structural properties sustaining such functions. Indicators of coherence 698 describe the degree of interaction between components or subsystems within an 699 agroecosystem, and connectedness describes interactions with adjacent systems (i.e., other 700 agroecosystems, urban or natural systems, etc.). When several indicators are considered 701 simultaneously, it may be pertinent to check whether all the relevant criteria pertaining to 702 system performance, diversity, coherence or connectedness are given equal importance. For 703 example, López-Ridaura et al. (2002) and Pacini et al. (2003) used two sets of indicators in 704 two independent evaluations of agroecosystems. Although both methods considered multiple

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criteria pertaining to system sustainability, they weighted thevarious system properties and/ordimensions of sustainability differently.

707

708 In general, comparative analyses based on indicators providea static picture of the status of 709 agroecosystems at one particular point in time, without considering the underlying feedback 710 and system dynamics responsible for bringing the system to its current status and for any 711 subsequent change to that status. Beyond comparing multiple indicators and the tradeoffs 712 between them, the comparative analysis of agroecosystems should aim to distil the 713 relationships between relevant properties; e.g., between performance on the one hand, and 714 diversity, coherence and connectedness on the other. A common denominator of the indicators 715 used in multi-criteria evaluations is their interdependence and their dependence on the 716 structural diversity of the agroecosystem. This interdependence results from the co-adaptation 717 of agroecosystem components over time. The structural diversity 718 ofagroecosystems, corresponding to the diversity of system components and their 719 interrelationships, is only functional when organised in a specific way.

720

721 <u>3.2.2 Analysing the structure and functioning of agroecosystems</u>

722 It is often postulated that the ecological intensification of agroecosystems may be achieved 723 through gradual diversification to capitalise on regulatory principles and mechanisms inherent 724 to natural ecosystems (see above and, for example, Altieri, 1999; Gliessman, 2001; Wezel et 725 al., 2009). Knowledge of the structural diversity of an agroecosystem, however, may not be 726 sufficient to explain its behaviour, and the way in which the diverse components of the system 727 relate to each other should also be known. Moreover, unnecessarily high degrees of diversity 728 of system components and flows within systems with poorly organised configurations may 729 lead to redundancy (Kauffman, 1995; Ulanowicz, 2004). Here, we examine some methods for studying the diversity and organisation of system components based on the theory of networksthat may be used in the comparative analysis of agroecosystems.

732

733 Indicators of networkcomplexity and organisation have beenderived from communication 734 science. They were first used in economics by Leontief (1951, 1966), and later introduced into 735 ecology by Hannon (1973). Indicators, such as average mutual information (AMI) and 736 ascendency (A), were proposed by Ulanowicz (1997, 2004) for characterisation of the 737 development capacity (in terms of increased organisation) of ecological systems, and have 738 recently been used in comparative analyses of agroecosystems (Rufino et al., 2009). 739 Thisapproachis known as ecological network analysis, and Rufino et al. (2009)presented aset 740 of indicators including AMI, A, and Finn's cycling index, for assessment of the diversity and 741 organisation of system components governing N flows and food self-sufficiency in three 742 smallholder crop-livestock systems from Ethiopia, Kenya and Zimbabwe. Farm systems are 743 conceptualised as networks, with the household and the farming activities represented 744 ascompartments and the N flows represented as connections between compartments. In this 745 example, indicators assessing network size, activity, cycling, organisation and diversity of the 746 N flows were compared with indicators of productivity and household food self-sufficiency. 747 This analysis revealed that although the amounts of N cycled were small and similarat all 748 sites, resource use efficiency and dependence on external resources differed widely between 749 these apparently 'comparable' agroecosystems. System performance was positively related to 750 N flow network size, organisation and N cycling, consistent with the hypothesis that 751 increasing the organisation of resource cycling within resource-limited agroecosystems may 752 render these systems more adaptable and less vulnerable.

754 The main hypothesis underlying the use of these indicators is that agroecosystems retain the 755 properties of the natural ecosystems for which these indices were derived. Ulanowicz (2004) 756 calculated the value of several indicators of network size and organisation, such as the number 757 of different nodes and flows, their roles and their connectivity, for a number of natural 758 ecosystems and agroecosystems. This exercise revealed wider gaps between these systems in 759 terms of indicators of organisation than for the magnitude of energy matter and information 760 flow within them. In other words, increasing organisation makes it possible to do much more 761 with the same resources, while contributing to system stability. The extent and the manner in 762 which organisation contributes to building resilience in agroecosystems is a fascinating 763 research area that remains largely unexplored. Existing frameworks of thinking about 764 resilience in the field of ecology and nature conservation may also be of interest here (e.g., 765 Walker et al., 2010). An indirect measurement of the organisation of an agroecosystem is its 766 energy and entropy balance. Svirezhev (2000) proposed the use of thermodynamics concepts 767 to assess the sustainability of agroecosystems, based on the principle that an ecosystem in 768 equilibrium with its environment has a certain 'capacity' to absorb anthropogenic stress that is 769 regulated by its capacity to expel entropy back towards the environment (the 'entropy pump'). 770 This capacity, which emerges from various agroecosystem properties, can be used to 771 characterise the status of an agroecosystem with respect to the adjacent natural ecosystem 772 from which it has been derived.

773

Manyof the properties of agroecosystems are often interdependent, together determining thevulnerability and adaptation capacity of these systems in the face of external shocks and stressors (Luers, 2005). Far from being postulates of a new theory, these properties are discussed here as operational, working concepts. We know that the provision of agroecosystem service functions is regulated by the intrinsic properties of these systems, 779 thefunctionality of which can be influenced by design. In practical terms, 'design' implies 780 proposing alternative configurations for the organisation of energy, matter and information 781 flows towards, within and from the system in space and time. The examples examined here 782 indicate that, up to a certain critical level, an increase in the diversity of system components 783 and interrelationships confers desirable properties on agroecosystems consistent with the 784 paradigm of ecological intensification. However, these properties manifest themselves as 785 patterns in space and time that become more evident at particular scales and are often 786 described as variability and/or heterogeneity at other scales. Diversity and spatio-temporal 787 variability or heterogeneity are inherent to agroecosystems (Burel & Baudry, 2003), and may 788 represent constraints to the representation of these systems in prototyping or modelling, which 789 isoften based on modal agroecosystem configurations.

- 790
- 791 **4 Overall discussion and conclusion**

792 Wide new avenues seem to be opening up in agronomy to guide ecological intensification. 793 We have tried here to identify new sources of knowledge and methods and to consider their 794 potential role (Figure 1). The analysis, use and optimisation of biological regulation in 795 agroecosystems are the most commonly promoted methods of ecological intensification. This 796 approach frequently involves enlarging the foundations of agronomic knowledgeto cover 797 biotic components of the system and their interactions. This ecological analysis of the whole 798 system is of paramount importance, and further investment in this approach is required. This 799 will involve the expansion of agronomic knowledge through classical avenues of research, 800 involving the generation of data mostlythrough modelling and on-station experiments, and 801 their analysis through simulation studies or statistical hypothesis testing. Our proposed 802 approach is complementary to attempts to increase our understanding of biological regulations 803 in agroecosystems and to use this knowledgefor ecological intensification. Indeed, the 804 extension of sources of knowledge to natural ecosystems and farmers' knowledge relates 805 mostly tobiological regulation and is fundamentally consistent with the scientific approach to 806 acquiring knowledge about biological regulation in agroecosystems. The extension of sources 807 of knowledge to the results of plant sciences research is more debatable. For example, 808 Vanloqueren andBaret (2009) argued that genetic engineering closes off avenues 809 of agroecological innovation. However, plant science results are not inevitably linked to a 810 single technological regime. Agronomists, if they were aware of current knowledge in plant 811 sciences, could make use of some of this knowledge to rebalance technological regimes or to 812 construct new ones. The expansion of sources of knowledge will also indirectly promote ways 813 of generating data that are little used at the moment. Most agronomic data are still acquired 814 through on-station trials and modelling. The extension of sources of knowledge to farmers' 815 knowledge and natural ecosystems will highlightalternative methods of data generation. This 816 will, in turn, incite the development of new data processing methods, such as meta-analysis 817 and comparative studies.

818

The new avenues outlined here will require major methodological investment. Indeed, the extension of sources of knowledge suggested here is far from straightforward. Plant science results must be thoroughly screened by groups of agronomists and plant scientists working together, to identify the most promising results for use in ecological intensification. Three major points should be made:

(i) Most plant science knowledge of potential use in agronomy is based on genetic
drivers. As gene expression depends on environmental conditions, the use ofplant science
data in ecological intensification will require qualification and quantification of the
corresponding genotype x environment interactions, for a range of cropping systems, soils
and climatic conditions (see for example Spiertz *et al.*, 2007).

(ii) All dimensions of cropping system management may benefit from a greater
knowledge of plant biologyand soil ecology: crop rotation sequences, soil management,
crop management etc.Furthermore, most of the issues raised by ecological intensification
can be addressed: yield increase, cut-off forthe use of limited resources through better
mineral use efficiency, decrease in pesticide use through the adoption of new crop
protection methods, etc.

(iii) Our paper is limited to afew examples. To our knowledge, probably due to
schism betweenagronomists and plant scientists, no formal attempt to enlarge this list has
been made by systematically tracking plant science results of potential use in cropping
system design. Such tracking of results and the publication of the findings obtained would
nonetheless be of considerable interest.

840

The use of knowledge relating to natural ecosystems requires clarification concerning what to study and how, for each of the properties of agroecosystems that ecological intensification aims to improve. This suggests a possible step-wise course of action for agronomists seeking to mimic natural ecosystems:

- 845 Selection of the functions agronomists wish to improve (for example, nutrient cycle
 846 management);
- Identification, in natural ecosystems, of the structural characteristics (spatial
 heterogeneity, diversification of vegetation strata, variability of species in time and
 space, etc.) modifying these functions;
- B50 Definition of the qualitative or quantitative relationships linking properties and
 functions;
- Transposition of these functions to agricultural conditions;
- Use of these functions for the design of agroecosystems with specified aims;

Checkingthat the new agroecosystems express the targeted functions and have
 noundesirableproperties.

856 This procedure seems far more complex than simply trying to design agroecosystems "as857 similar as possible" to natural ecosystems.

858

859 Farmers' knowledge seems to be extremely valuable, and its use in association with scientific 860 knowledge requires appropriate processing by methods that are not yet well established. 861 Specific methods remain to be adapted from other domains or developed. The first 862 methodological requirement is a more profound analysis of local knowledge to determinewhich processes (ecological or otherwise) should beselected and how they can 863 864 beused or manipulated. Davis andRuddle (2010) analysed the ways in whichecological 865 knowledge (local, traditional or indigenous) is used and concluded that the same level of 866 scrutiny as for scientific experimental results should be applied before such knowledge is 867 accepted. However, this local knowledge is built within specific 'systems of knowledge' 868 (Davis & Ruddle, 2010), and thereforecannot be analysed purely in terms of its content 869 relevant to agronomy or ecological science. It must also be analysed from a social point of 870 view (which processes lead to this knowledge? How is it shared, transmitted etc.?). This 871 analysis calls for pluridisciplinary approaches. We also need to design approaches inspired by 872 or directly making use of the argumentation theory and methods developed in the domain of 873 artificial intelligence (Amgoud & Prade, 2009).

874

The use of meta-analysis methods for ecological intensification benefits from extensive experience in other research areas, and follows guidelines that have proved to be effective. Nevertheless, data acquisition in agronomy has not traditionally been organised with the requirements of subsequent meta-analyses in mind. As a consequence, considerable effort is required to adapt the methods to existing agronomic data and to establish guidelines for the generation of further data. Finally, comparative studies in agriculture often remain descriptive, and are not always oriented to identify the relationships between agroecosystem structure and functioning—undoubtedly a new challenge for agronomic research.Addressing this aim will require the development of guidelines for site selection, characterisation methods, data processing, etc.

885

Finally, each of the five topics outlined will probably require specific organisation within research institutes. They may also induce changes in academic curricula in agronomy, as plant scientists and agronomists currently follow different curricula, with little in the way of shared knowledge, concepts and technical skills.

890

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892

893 **Figure captions**

894 Figure 1. Summary of new avenues of agronomic research for ecological intensification



Figure 2. A comparison of natural ecosystems, conventional cropping systems and
agroecosystems inspired from natural ecosystems, with an emphasis on crop protection



903 Tables

Table 1. Examples of recent results fromplant sciences useful in agronomy

Topics inplant sciences	Key references	Potential agronomic benefits		
Plant architecture	Zhu <i>et al.</i> (2010) Walter <i>et al.</i> (2009)	Increased radiation interception		
	dePury& Farquhar (1997)			
Photosynthesis efficiency	Wang & Li (2008)	Canopy pattern target for crop management Increase in yield		
		Identification of genotypes adapted for crop mixture		
Exchanges of nitrogen between roots and environment	Jackson et al. 2008	Improved fertiliser use efficiency		
Role of organic anion	Glass (2003)	Improved nitrogen management		
exudation	Ryan <i>et al.</i> (2001)			
Interaction between roots and soil	Mehboob et al. (2009)	Improved mineral nutrition		
organisms	Brussaard et al. (2007)			
Role of common mycorrhizal networks	Micallef et al. (2009)	Improved crop growth		
5	Ryan et al. (2009)	Adaptation of crop management		
	Sturz and Nowak (2000)			
	Van der Heijden & Horton (2009)			
Interaction between aerial parts of the plant and environment	De Bruxelles & Roberts (2001)	Management of natural defences for improved resistance to pests		

908 Table 2. Examples of farmers' knowledge potentially useful in agronomy

Sources of knowledge	Key references	Potential agronomic benefit
Local ecological knowledge	Chalmers & Fabricius (2007)	Explaining changes in agricultural systems
Traditional farming systems	Singh & Sureja (2007) Abbona <i>et al</i> . (2007)	Design of sustainable farming systems Understanding of ecological processes
Local knowledge and indicators for assessing forest management	Ballard <i>et al.</i> (2008)	Assessment of management practices for forests
Farmer's indicators supporting decision making	Tchamitchian <i>et al</i> . (2006)	Indicators with expanded domains of validity

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