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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 various ecosystem services and to resolve apparent conflicts between them. 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 sciences over the last
35 two decades provides new insight of potential use to agronomists. 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
38 ecosystems may also provide sources of inspiration for cropping system design, in terms of
39 their structure and function on the one hand, 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
46 remaining avenues concern methods. We suggest that agronomists make more use of meta-
47 analysis and comparative system studies, these two types of methods being commonly used in
48 other disciplines but barely used in 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

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

56

57

58

59

60 **1. Introduction**

61

62 New agricultural systems are required to allow agriculture to satisfy the increasingly
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 to include other ecosystem services (Zhang *et al.*, 2007). Like other natural and semi-artificial
67 ecosystems, agroecosystems can provide services, such as carbon sequestration, pollination,
68 or water filtration. The capacity of agriculture to provide such services is, of course, not
69 always guaranteed, and there are many examples of adverse effects of agricultural practices on
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.

76

77 Agronomists have argued that the mission of multi-objective agriculture could best be
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 use more 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.

92
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
96 focuses principally on the fate of fertilisers and their use by crops. Witt *et al.* (2006) applied a
97 similar approach to oil palm plantations. According to Chevassus-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 based on “intensification in the use of
103 the natural functionalities that ecosystems offer”. Though relatively vague, this definition
104 remains a possible starting point for the consideration of alternative pathways of development
105 for agriculture. This definition is much broader than that of Cassman (Cassman, 1999), and
106 provides an interesting haven for scientists promoting the use of biological regulation in
107 agroecosystems.

108

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 individual physical 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; Lançon *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 agroecosystems and (iii) embracing local farmers’ knowledge. Methods for
125 assessing these sources of knowledge are necessarily diverse, and could be 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 knowledge for
129 agronomists and data processing methods.

130

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

132 **2.1 – Mobilizing advances 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 to dissect 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 science to design ecologically intensive cropping systems.

143

144 2.1.1. A new look at the basics

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
153 cropping system design. Moreover, the more sophisticated representations of the basic
154 processes of plant life implemented in more complex models do not necessarily improve the
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

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

160

161 Nutrient use efficiency is also clearly 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
170 may account, at least in part, for the high variability of fertiliser efficiency observed in field
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.

176

177 2.1.2. The cultivated plant and its biological environment

178 Since the middle of the last century, the gradual “artificialisation” of agriculture has led to
179 agronomists paying less attention to the biological components of fields. Agroecology has
180 emerged as a reaction against this excessive simplification of the system, placing the
181 biological component back at the heart of the system (Altieri, 1989), and resulting in the
182 development of an “agroecosystem” view (Conway, 1987). Nevertheless, common agronomic

183 practices still largely ignore biological interactions in cultivated fields, and agroecologists
184 often emphasise the need for an empirical and holistic approach to agroecosystems. New
185 findings in plant sciences concerning the relationships between the plant and its surrounding
186 biotic environment have recently emerged and are of great interest.

187

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
217 benefits of these associations with endophytic rhizobacteria depend on the survival of
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).
228 The networks that these fungi establish between plants may provide a major route for mineral
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
232 CMN development, but that there were also large differences in the benefits accrued,

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).

244

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
248 Bruxelles & Roberts, 2001; Kessler & Baldwin, 2002). Some result in the production of
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.

256

257 2.1.3. Ways to improve the use of plant sciences for ecological intensification

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, concerning plant 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 productive cropping systems.

275

276 Finally, there are many different drivers of change in ecological intensification (see
277 introduction and subsequent sections). Innovative systems that have already been developed
278 in the domain of ecological intensification, such as the use of mixtures of cultivars or species,
279 agroforestry and no-tillage systems, would certainly benefit from the knowledge provided by
280 plant sciences. However, these systems will themselves raise new questions and issue new
281 challenges to plant science. For example, although progress has been made in this area, plant
282 sciences results are still often obtained in highly simplified systems and therefore cannot easily

283 be translated to multispecies systems. Above-ground competition for light and below-ground
284 competition for water are major processes in ecological intensification that require study in
285 systems including facilitation between plants (Long & Nair, 1999; Zhang *et al.*, 2008;
286 Malézieux *et al.*, 2009).

287

288 **2.2 - Learning lessons 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
301 was followed in the framework of Ecoagriculture, proposed by McNeely and Scherr (2003),
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.

311

312

313 2.2.1 What does “Mimicking natural ecosystems” mean?

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 vegetation structure 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 systems provide both 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

333 Cameroon or Costa Rica, are original ways in which farming communities use natural
334 resources in human reconstructions of both "natural" and productive ecosystems from natural
335 ecosystems (Michon *et al.*, 1995, 2007; Schroth *et al.*, 2001, 2004).

336

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 Noordwijk
340 and Ong (1999) proposed two principles for the design of agroecosystems based on natural
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 agroecosystem 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

351 According to the second principle, the redesign of agroecosystems in more ecologically
352 intensive configurations implies their diversification. This has been the case, for example, in
353 Cuba, where small- and medium-scale farmers have tended to diversify their production
354 systems in response to their limited access to or total lack of agricultural inputs to sustain
355 productivity (Funez-Monzote *et al.*, 2009). The resulting diversified systems are energetically
356 more efficient, less dependent on external inputs, more productive, adaptable and resilient.
357 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 out by 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 for evaluation.
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 landscape may 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 to achieve different goals. Consequently approaches mimicking
380 natural ecosystems are limited by certain agricultural 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 a
383 dimension absent from natural ecosystems: human agency.

384

385 2.2.2 Agroecosystems as complex socio-ecological systems

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*
393 *al.*, 2004). This is why agroecosystems may be defined as socio-ecological systems, or
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 broadest sense thus concerns the diversity of livelihood strategies at a 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 expertise valorisation 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 to Prior (2003), we may consider farmers to be *lay experts* (although this
427 denomination entails an antinomy): *experts* because of their experience-based knowledge
428 and *lay* because this knowledge is limited in scope and does not give farmers the 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

432 as interpreted by the patient) and industry (particularly for fault detection in plant or machine
433 operation). However, although the value of this lay expertise is recognized, it is not used to
434 build or extend the current scientific knowledge, but to adapt its application in local situations
435 (Henderson, 2010).

436

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 gain experimental 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

456 the available scientific agronomic knowledge (see the examples presented in Table 2). We
457 will defend this point and discuss the various issues it raises below.

458

459 2.3.1. Value of farmers' knowledge for agronomy

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 developed over 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 help to enlarge current agronomic
465 knowledge in various ways. 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 for ecological intensification. Chalmers & Fabricius (2007), for example, showed that local
474 experts, using their ecological knowledge, were able to put forward explanations for changes
475 in their system, some of which were also provided by scientific knowledge. However, the local
476 experts also had other explanations rooted in a more general understanding 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 was indeed 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
493 and efficient means of assessing the effects of management practices on the forest. The same
494 was found for greenhouse tomato management. 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 crop vigour 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 and its ability to perform
500 photosynthesis (Navarrete *et al.* 1997), without being able to model it formally.

501

502 Taken as a whole, local knowledge and lay expertise can provide clues to the natural or
503 ecological processes most useful in the design of sustainable farming systems, such as the
504 natural regulation of pest populations by their predators (Barzman *et al.*, 1996; Sinzogan *et al.*
505 2004), or management of the soil and its mineral balance (Steiner, 1998; Okoba & de Graaf,

506 2005; Saito *et al.*, 2006; Abbona *et al.*, 2007). They can also be of value in the design of
507 assessment methods or indicators for monitoring the ecological performances of these farming
508 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 a panel 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 particularly when 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 the variables 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 out by Prior (2003), lay
528 experts may be 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 (ranges of 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 precision raised
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
568 knowledge and that of the lay expertise yielding the rule were different.

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 The data generated are then processed, mostly by classical methods, such as simulation studies,
579 single-experiment data analysis, or group analysis. These methods could probably be
580 complemented with two other methods: meta-analysis, involving the statistical synthesis of

581 results from a series of studies, and comparative analyses of agroecosystems, involving the
582 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 the between-study variability of a variable of interest.

588

589 Both scientific researchers and decision-makers can benefit from meta-analysis in several
590 ways (Sutton *et al.*, 2000), as this approach provides a methodological framework for (i)
591 exploring what has already been done on a given research topic and identifying more clearly
592 where the gaps and uncertainties lie, (ii) generating an overview of divergent results, (iii)
593 guiding decisions based on a systematic review and statistical analysis of all the available data
594 related to a given topic, (iv) broadening the knowledge base and allowing replication for the
595 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; Cardinale *et al.*, 2006), and has
600 sometimes been applied in agriculture (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 describe quantitatively 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 over several 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 mean yield ratio for
618 various food categories, for both developed and developing countries.

619

620 Diverse techniques for meta-analysis are available (e.g., Borenstein *et al.* 2009; Sutton *et al.*,
621 2000), but meta-analysis should always include the following steps:

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

- 630 iv. Assessment of between-study variability and heterogeneity. Evaluation of the
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
636 example, can be achieved by calculating a weighted sum of individual
637 estimates derived from the studies collected in step ii.
- 638 v. Assessment of publication bias. Publication bias occurs when only studies with
639 highly significant results are published. In this case, a meta-analysis can lead to
640 a biased conclusion and overestimation of the effect of a given factor. The
641 ‘funnel plot’ technique can be used to deal with this issue (e.g., Borenstein *et*
642 *al.*, 2009).
- 643 vi. Presentation of the results and of the level of uncertainty.

644

645 In the context of ecological intensification, the meta-analysis framework constitutes an
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 for crop
648 production (e.g., Jones & Thornton, 2003) and to assess the effect of cropping systems on
649 key environmental variables (e.g., Rolland *et al.*, 2008), two key issues for ecological
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

655 data is available for such purposes (e.g., Rochette & Janzen, 2005). Such data could be
656 reviewed, combined and analysed with statistical techniques, to rank cropping systems as a
657 function of their impact on key environmental variables, such as water nitrate content,
658 greenhouse gas emissions (e.g., N₂O) and the presence/absence of species of ecological
659 interest (e.g., earthworms, birds). However, meta-analysis requires the use of appropriate
660 techniques and the value of a meta-analysis may be greatly decreased if the six steps outlined
661 above are not rigorously implemented.

662

663 **3.2. Comparative analysis of agroecosystems**

664 Information useful 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 display specific system properties. Several
672 approaches have been proposed for this purpose (e.g., Pannell 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) and Marten
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

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

685

686 3.2.1 Comparative analysis based on multiple indicators

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
691 stakeholders, so ‘quality control’ methods for evaluating the choice of indicators are
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

705 criteria pertaining to system sustainability, they weighted the various system properties and/or
706 dimensions of sustainability differently.

707

708 In general, comparative analyses based on indicators provide a 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 of agroecosystems, corresponding to the diversity of system components and their
719 interrelationships, is only functional when organised in a specific way.

720

721 3.2.2 Analysing the structure and functioning of agroecosystems

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

730 studying the diversity and organisation of system components based on the theory of networks
731 that may be used in the comparative analysis of agroecosystems.

732

733 Indicators of network complexity and organisation have been derived 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 ascendancy (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 This approach is known as ecological network analysis, and Rufino *et al.* (2009) presented a set
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 as compartments 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 similar at 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.

753

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

774 Many of the properties of agroecosystems are often interdependent, together determining
775 the vulnerability and adaptation capacity of these systems in the face of external shocks and
776 stressors (Luers, 2005). Far from being postulates of a new theory, these properties are
777 discussed here as operational, working concepts. We know that the provision of
778 agroecosystem service functions is regulated by the intrinsic properties of these systems,

779 the functionality 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 is often 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 knowledge to 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 mostly through 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 knowledge for ecological intensification. Indeed, the

804 extension of sources of knowledge to natural ecosystems and farmers' knowledge relates
805 mostly to biological 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 science research is more debatable. For example,
808 Vanloqueren and Baret (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 highlight alternative 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

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

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

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

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

840

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

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

854 - Checking that the new agroecosystems express the targeted functions and have
855 noundesirableproperties.

856 This procedure seems far more complex than simply trying to design agroecosystems “as
857 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
863 determinewhich processes (ecological or otherwise) should beselected and how they can
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

875 The use of meta-analysis methods for ecological intensification benefits from extensive
876 experience in other research areas, and follows guidelines that have proved to be effective.
877 Nevertheless, data acquisition in agronomy has not traditionally been organised with the
878 requirements of subsequent meta-analyses in mind. As a consequence, considerable effort is

879 required to adapt the methods to existing agronomic data and to establish guidelines for the
880 generation of further data. Finally, comparative studies in agriculture often remain
881 descriptive, and are not always oriented to identify the relationships between agroecosystem
882 structure and functioning—undoubtedly a new challenge for agronomic research. Addressing
883 this aim will require the development of guidelines for site selection, characterisation
884 methods, data processing, etc.

885

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

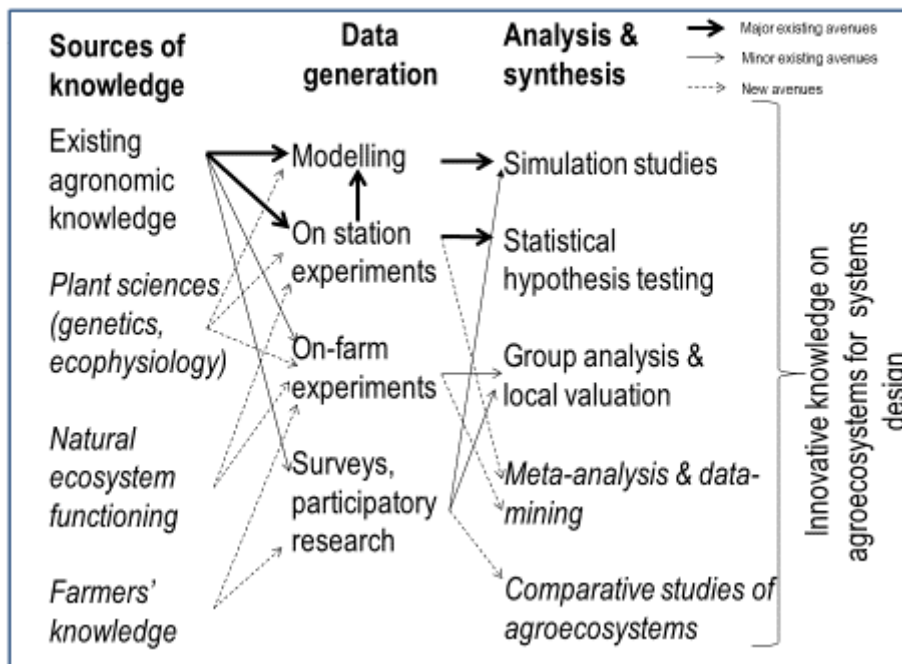
890

891 **Acknowledgement:** we thank Alain Bône and Julie Sappa for their skilled assistance.

892

893 **Figure captions**

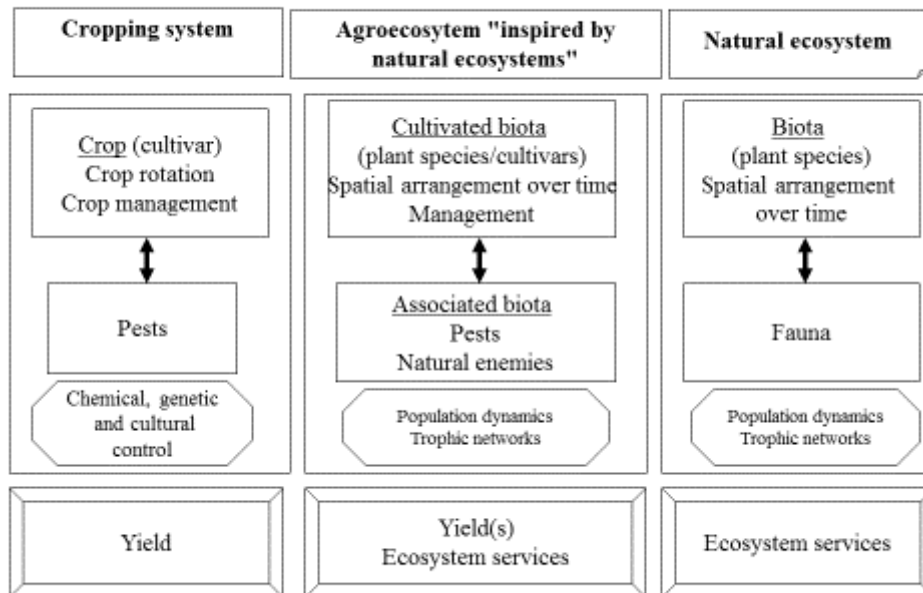
894 **Figure 1.** Summary of new avenues of agronomic research for ecological intensification



895

896

897 **Figure 2.** A comparison of natural ecosystems, conventional cropping systems and
 898 agroecosystems inspired from natural ecosystems, with an emphasis on crop protection
 899



900

901

902

903 **Tables**

904

905 **Table 1.** Examples of recent results from plant sciences useful in agronomy

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

906

907

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) | Design of sustainable farming systems |
| | Abbona <i>et al.</i> (2007) | 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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