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Global agronomy, a new field of research. A review

David Makowski, Thomas Nesme, François Papy, Thierry Doré

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Agronomy for Sustainable Development

Global agronomy, a new field of research. A review.

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Abstract:	<p>The global impact of agriculture has recently become a major research topic, stressed by the rapid growth of the world population. Agriculture management is indeed influencing the quality of water, air, soil and biodiversity at the global scale. The main agricultural challenges have already been reviewed, but these reviews did not discuss in detail the adaptations of agricultural techniques to global issues and the research challenges for agronomy. Here we propose a research planning for global agronomy including the following advices. Agronomists should update their research objects, methods and tools to address global issues. Yield trends and variations among various regions should be analyzed to understand the sources of these variations. Crop model simulations should be upscaled to estimate potential yields and to assess the effect of climate change and resource scarcity at the global scale. Advanced methods should analyze output uncertainty of complex models used at a global scale. Indeed various global models are actually used, but these models are too complex and the output uncertainty is difficult to analyze. The meta-analysis of published data is a promising approach for addressing global issues, though meta-analysis must be applied carefully with appropriate techniques. Finally, global datasets on the performance and environmental impact of cropping systems should be developed to allow agronomists to identify promising cropping systems.</p>
Author Comments:	<p>Dear Editor,</p> <p>We thank you again for taking time to consider this revision and giving us the opportunity to revise the paper. All the suggestions made by the Editor-in-chief have been taken into account.</p> <p>We hope you will consider that your comments were appropriately addressed.</p> <p>Sincerely yours,</p> <p>David Makowski (on behalf of the co-authors)</p>

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- Pourriez-vous, s'il vous plait, insérer une photo couleur dans l'introduction ?

Nous pensions que la carte du monde mentionnée en introduction pourrait faire office de photo mais, comme cela ne semble pas être le cas, une photo illustrant la croissance démographique a été ajoutée dans la version révisée de l'article (Figure 1).

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1 **Global agronomy, a new field of research. A review.**

2

3 **David Makowski^{1,2}, Thomas Nesme^{3,4}, François Papy^{5,6}, Thierry Doré^{2,1}**

4

5 ¹ INRA, UMR 211 Agronomie, F-78850 Thiverval-Grignon, France

6 ² AgroParisTech, UMR 211 Agronomie, F-78850 Thiverval-Grignon, France

7 ³ Univ. Bordeaux, UMR 1220 TCEM, F-33175 Gradignan, France

8 ⁴ INRA, UMR 1220 TCEM, F-33882 Villenave d'Ornon, France

9 ⁵ INRA, UMR 1048 SADAPT, BP 01, Thiverval-Grignon, France

10 ⁶ AgroParisTech, UMR 1048 SADAPT, BP 01, Thiverval-Grignon, France

11

12 **Corresponding author:**

13 David Makowski

14 INRA, UMR 211, BP 01 78850 Thiverval-Grignon, France

15 Tel: 33 1 30815992

16 Fax: 33 1 30815425

17 E-mail: makowski@grignon.inra.fr

18

19

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21

22 **Abstract**

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35 approach for addressing global issues, though meta-analysis must be applied carefully with
36 appropriate techniques. Finally, global datasets on the performance and environmental impact of
37 cropping systems should be developed to allow agronomists to identify promising cropping systems.

38 **Key-words:** agronomy, food security, global changes, modeling

39

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61 **1. Introduction**

62 The impact of agriculture has long been studied at the local scale by agronomists. Many experiments
63 have been carried out to assess the effect of one or a small number of aspects of crop management
64 (e.g. soil tillage, fertilizer rates, etc.) on one or a small number of variables of interest (e.g. yield, soil
65 characteristics). Experiments have also been carried out to compare and assess cropping systems at
66 the field and, in a few cases, farm scales (Vereijken 1997). Since the late 1980s, modeling tools have
67 been used to optimize agricultural practices at the field and farm scales and, in few cases, at the
68 regional or continental scales (van Ittersum et al. 1998; de Wit et al. 1988).

69 However, the effect of agricultural activities at the global scale has recently become an important
70 research topic. This shift is due to the large growth of the world population (Spiertz 2012) (Figure 1)
71 and increasing concerns about air, soil and water quality, the fate of biodiversity and resource
72 management (Mueller et al. 2012; Tschardtke et al. 2012). Agriculture has to deal with greater and
73 emerging challenges relating to food security and its impact on the global environment. The effect of
74 nitrogen fertilization on greenhouse gas emissions (Philibert et al. 2013), the global phosphorus
75 resource depletion, the estimation of future crop yield trends (Lobell and Burke 2010), yield gap
76 analysis at the global scale (Mueller et al. 2012), and the impact of invasive pests (Dupin et al. 2011)
77 are examples of research topics that have recently emerged and are now studied by major
78 agricultural research institutes. The results of these new investigations are frequently used in
79 prospective studies on food security (Paillard et al. 2010) and global environmental issues, such as
80 global nutrient flows (Gruber and Galloway 2008), global warming (Parry et al. 2007), and
81 biodiversity loss (Tschardtke et al. 2012). Prospective studies, such as Agrimonde (Paillard et al. 2010)
82 are based on diverse scenarios based on different hypotheses concerning future food demand, food
83 production levels and impacts of agriculture on the environment. Scenarios about future cropping

84 systems are therefore required in prospective studies, and agronomists are now frequently asked to
85 provide data on future agricultural practices, and on future levels of crop productions (Figure 2).

86 These recent changes present agronomy with both opportunities and challenges. Agronomists have
87 the opportunity to deal with important global issues and to become important players in groups of
88 scientists working on food security and environment and resource protection. However, they will
89 also face major challenges if they are to provide a useful contribution to the current research on
90 global issues. Agronomists need to jump from references established for crop production and the
91 environmental impact of agriculture at local scales to new references for use at larger scales. They
92 also need to find effective ways to communicate their results to other scientists (particularly
93 economists and climatologists), developing models simulating the impact of agricultural activities at
94 the regional, continental and global scales.

95 Several reviews on global food security have recently been published (Spiertz 2012; Tscharrntke et al.
96 2012). They present the principal challenges to be faced by agriculture in the next few decades.
97 However, they do not discuss the ways in which current agricultural research methods would need to
98 be adapted to deal with global issues. We present here a research agenda for global agronomy. We
99 show that agronomists need to reconsider their research objectives and to update their research
100 tools before addressing global issues. Below, we present examples of topics that should be
101 investigated at the global scale. We then review the types of data already produced by agronomists
102 and assess the value of these data for studying the effect of agricultural activities at the global scale.
103 Finally, we present various methods for addressing global issues in agronomy, and analyze their
104 advantages and disadvantages.

105

106 **2. Addressing new questions**

107 Two examples of global issues in agriculture are presented below. We show that these issues create
108 new research objectives and pose new research questions that need to be addressed by agricultural
109 research institutes.

110 ***2.1. Global nutrient management***

111 In the last decades, fertilizer applications to enhance crop production have been seen as agents of
112 environmental damage, causing nitrate leaching, eutrophication and greenhouse gas emission. Their
113 use was supported by the design of field-scale decision rules and crop models (van Ittersum and
114 Donatelli 2003), and by the assessment of nutrient flows at catchment scale. However, recent
115 concerns have emerged about the finite nature of global phosphorus (P) resources (Cordell et al.
116 2009; Van Vuuren et al. 2010) and the huge amount of reactive nitrogen (N) accumulating in the
117 biosphere at global scale (Galloway et al. 2008). Both these phenomena are due to the massive use
118 of mineral N and P fertilizers in agriculture (Bennett et al. 2001; Sutton et al. 2011; Tilman et al.
119 2002). Such issues raise new questions, concerning identification of the different drivers of global
120 fertilizer use, for example (Sattari et al. 2012). Reports have indicated that nutrient cycle closure is
121 relatively weak at the country scale, in many different contexts (Liu et al. 2008; Mishima et al. 2010;
122 Senthilkumar et al. 2012a) due to both a large proportion of organic waste being not recycled to
123 agricultural soils (Elser and Bennett 2011) and to a high degree of specialization and of spatial
124 segregation of animal and feed production systems affecting nutrient flows and budgets (Grote et al.
125 2005; Liu et al. 2010; MacDonald et al. 2011; Naylor et al. 2005) and making it impossible to replace
126 mineral fertilizer with animal manure (Senthilkumar et al. 2012b).

127 New research objectives are required to deal with this issue. Studies assessing the consequences of
128 food/feed demand (e.g. the proportion of animal products in human diets, food losses, food chain
129 design) on global nutrient flows are required. This would involve dynamic models simulating the

130 effects of food diets on crop production requirements and ultimately on fertilizer use. It would also
131 be necessary to assess the consequences of the spatial organization of global feed and animal
132 production basins and to study the effects of livestock feeding regimes on changes in land use in
133 regions of feed production (e.g. soy production in South America) and their environmental
134 consequences. Finally, research needs to pay more attention to the possibilities for waste recycling
135 (e.g., from the food industry or wastewater management) in agriculture, focusing, in particular, on
136 the conditions required for the effective replacement of mineral fertilizers with organic materials
137 derived from waste products.

138 **2.2. Global food security**

139 The food production dimension of food security is another important issue for agronomists. Crop
140 yield increase rates are key parameters for foresight studies on food security (Paillard et al., 2010),
141 and their values are very variable both spatially (Figure 2) and temporarily (Figure 3). In the past,
142 crop production and its variability were studied at field scale by means of experiments and of crop
143 models simulating the effect of cropping techniques on crop yield. However, tackling food production
144 at a global scale requires significant changes in research objectives, particularly as concerns climate
145 change. The effect of climate change on global food production has been investigated in many
146 studies (Lobell and Burke 2009). Such studies require three types of data: (i) data on future climatic
147 conditions, (ii) data on the effect of climatic variables on crop production, and (iii) data on the effect
148 of climatic variable on land use and cropping practices. For illustration, data quantifying the effect of
149 climate change on wheat yields were extracted from 90 published papers retrieved from the Web of
150 Knowledge between 1991 and 2012, and were displayed in Figure 4. These data represent relative
151 yield changes defined by $RCY = 100 * (\text{future average yield} - \text{baseline average yield}) / \text{baseline}$
152 average yield , where “baseline average yield” and “future average yield” correspond to simulated
153 yield values averaged over years for both baseline and future climatic scenarios. Simulated yields
154 were generated using different types of crop models for different climate change scenarios in several

155 countries. The median RCY reported in the 90 published papers ranged from -4.5% (Spain) to +15%
156 (India) (Figure 4). The variability of RCY was very strong within a given country, especially in countries
157 where the number of reported data was high. For example, RCY ranged from -100% to +90.8% in
158 Australia and from -97.6% to + 155.8% in USA. This result shows that simulated climate change
159 impact on yield can be very different depending on the location, the considered crop models, and the
160 climatic scenarios.

161 Contrary to data of types (i) and (ii), data on agricultural land use and cropping practices are scarce,
162 particularly for larger scales. For this reason, the effects of climate change on crop production are
163 usually estimated for potential yields only, and the effects of other limiting factors are rarely taken
164 into account.

165 More generally, the global food security issue raises questions about the production capacities of
166 various types of farming systems (organic, intensive, integrated etc.) and their ability to satisfy the
167 demand for food. For instance, the ability of organic farming to feed the world has been much
168 debated in recent years (de Ponti et al. 2012; Seufert et al. 2012; Badgley et al. 2007). Organic
169 farming scenarios have been compared with conventional systems on the basis of crop yield ratios
170 (organic vs. conventional) determined at the field scale for various sites. However, the ratio-based
171 approach has several limitations. For example, it does not take into account the transition between
172 current levels of organic farming (approximately 1%) to a future 100% organic global farming system
173 or the spatial interactions between organic and conventional cropping systems (e.g. the effects of
174 conventional spraying on pest dynamics might indirectly provide pest control for organic cropping
175 systems;(Norton et al. 2009; Ricci et al. 2009; Roschewitz et al. 2005; Thies and Tscharntke 1999).
176 Organic farming extension raises questions about the effectiveness of legume N fixation, use of
177 organic materials, and soil nutrient depletion to replace mineral fertilizer. The capacity of the current
178 agricultural area to fix enough N to sustain crop production and the ability of organic farming to
179 make use exclusively of soil P mining and P recycling without external P input from chemical

180 fertilisers have not been precisely quantified (de Ponti et al. 2012; Doberman 2012). Therefore, the
181 transition from conventional to organic land use might increase competition for nutrients derived
182 from organic fertilizers at the regional scale (Nesme et al. 2012).

183 Besides the global food security issue raises questions about spatial distribution of crops and
184 cropping systems at the global scale under scenarios of climate or farming system change. It also
185 highlights the need to deal with regional questions, such as spatial interactions between farming
186 systems in terms of nutrient availability or pest/enemy relationships and the scaling-up of such
187 interactions.

188 Table 1 lists a series of new scientific questions for global agronomy, using the two examples
189 presented above.

190

191

192 **3. Current knowledge and methods in agronomy: their utility and** 193 **limitations for addressing global issues**

194 Many agronomic studies worldwide still make use of surveys, experiments and modeling. An
195 exhaustive analysis of the literature is impossible, as this would require the examination of tens of
196 thousands of articles. However, a qualitative approach to the topics covered by agronomic research
197 can nevertheless be attempted.

198 ***3.1. Knowledge on how agroecosystems work***

199 Most agronomic studies are carried out at the field scale. It is easy to find examples of such studies in
200 any issue of the major agronomy journals (Harunur Rashid et al. 2012; Krueger et al. 2012; Nakano et
201 al. 2012). Many studies in the second half of the 20th century focused on the effects of soil tillage,

202 crop rotation, irrigation, fertilizer application, crop protection strategies, crop density, date of sowing
203 and, of course, genotype. Over the last two decades, new variables have emerged, such as the effect
204 of mixing species (Malezieux et al. 2008) or the use of new types of fertilizers (Cavanagh et al. 2011).
205 Attention has also shifted onto new topics, such as nonfood uses of crop products and the impact of
206 agriculture on environmental resources or ecosystem services (Otieno et al. 2011). These trends are
207 a consequence of the diverse major challenges currently facing agriculture and the need for changes
208 in agricultural systems, which may not in themselves be sufficient (Foley et al. 2011).

209 An increasing number of studies are comparing entire cropping systems rather than just a few sets of
210 techniques (e.g., a few fertilizer doses and a few cultivars), through experiments, model simulations,
211 or both (Rossing et al. 1997). For example (Farooq et al. 2011) considered the effects of conservation
212 and conventional agriculture, whereas (Michos et al. 2012) compared organic, integrated and
213 conventional orchards, in a similar way to (Reganold et al. 2001). Unlike experiments considering
214 only a limited number of technical elements, cropping system studies acknowledge that the effect of
215 a single technique cannot be reliably predicted if the other techniques of the cropping system are not
216 taken into account (Doré et al. 1997). These studies aim to bridge the gap between simplified
217 experiments and the real farming. However, the generic value of cropping system studies is
218 decreased by the lack of specificity of cropping system names, such as “conventional systems”,
219 “organic systems” and “integrated systems” since many different practices are covered by such
220 names.

221 More recently, agronomists have enlarged both their spatial and temporal scales of investigation.
222 Some experiments are now also carried out at larger scales, particularly at the scale of the landscape.
223 A few decades ago, agronomists began to address environmental issues, such as soil erosion and
224 water pollution (Jones et al. 1990; Knickel 1990). They recently began studying the effects of land use
225 or cropping patterns on ecological processes (Ricci et al. 2009; Thies et al. 2011). Over the same
226 period, interest has increased in medium-term (e.g. several years; (Enfors et al. 2011) and long-term

227 (e.g. several decades; (Yang et al. 2011) assessments of cropping systems, and this has led to some
228 methodological progress (Brandt et al. 2010). Such changes in time scale are driven by the fact that
229 many ecosystem services (e.g. carbon sequestration) must be considered over the long term,
230 together with the anticipation that some effects of cropping systems are unlikely to be evident
231 immediately, instead being expressed only after stabilization of the agroecosystem.

232 Models simulating the effects of cropping systems on agroecosystems from field to regional scale
233 and from year to decades are of key importance for global agronomy. Such models would facilitate
234 the assessment of effects of changes in agricultural systems, or the design of new agricultural
235 systems. For instance, estimates of N₂O emissions by the Tier 1 to Tier 3 methods (Eggleston et al.
236 2006) were used by the International Panel on Climate Change in their prospective studies dealing
237 with greenhouse gas emission and climate change.

238 Another example is provided by the issue of fossil P reserve depletion, which may lead to a shortage
239 of P fertilizer and a potential decrease in soil P availability at global scale. This raises questions about
240 the effects of such decreases on long-term global food production. Recent studies have reported
241 current or future soil P budgets (soil P input minus soil P output) on a 50 km x 50 km grid, based on
242 fertilizer use and livestock density statistics (MacDonald et al. 2011; Van Vuuren et al. 2010).
243 However, there is a gap in our knowledge between these budgets on the one hand and the
244 consequences in terms of global crop production on the other (Sattari et al. 2012). In the future,
245 existing field-scale soil and crop models could be used to relate soil P budget to soil P availability (e.g.
246 soil P concentration) in a large range of soil conditions and cropping systems (Messiga et al. 2012),
247 and then to predict crop yields for some crop species as a function of soil P availability (Mollier et al.
248 2008) (Figure 5). Linking global scale P budgets and existing field-scale models would, therefore, be
249 very useful for assessing the consequences of global current or future P fertilization practices in
250 terms of global crop production.

251 However, we have to push the limits of our current knowledge for addressing global issues. The
252 various possible combinations of climate, soil and technical conditions do not receive equal amounts
253 of attention in agronomic studies (for example, studies of “minor” crops, such as tuber or some
254 cereal crops, are scarce, despite the possible regional importance of these crops in the diet of the
255 population). This inequality partly reflects the differences in investment in agronomic research across
256 the world. In addition, some of the crucial topics for addressing global issues have been largely
257 neglected. For instance, studies on the effects of farming systems on pest dynamics across countries
258 and continents are much rare than studies considering pest control at the field scale.

259

260 ***3.2. Knowledge about farmers’ practices and the factors driving them***

261 Agronomists have long studied farmers' practices. Research studies have investigated the
262 interactions between the various practices and the factors driving farming practices (Fresco 1984;
263 Collinson 2000). In these studies, a farm is seen as a place where a farmer coordinates different
264 practices in a comprehensive and coherent way, to satisfy a set of goals. Studies on cropping system
265 management and landscape management (e.g. slashing, field and hedgerow patterns, irrigation and
266 drainage devices) have shown that complex processes underlie the decisions taken by farmers (Papy
267 2001) and that farmers’ decisions regarding crop rotations and cropping plans, as well as crop
268 management, can be formalized through decision rules and models (Cros et al. 2004; Aubry et al.
269 1998).

270 These studies have also highlighted the considerable diversity in farmers' goals and management
271 practices. Agronomists have developed farm clustering methods to describe farm diversity at the
272 regional scale. They have also developed and used user-friendly models to manage the rural
273 landscape in a collective manner, to reduce run-off and erosion, for example (Joannon et al. 2006), or
274 to introduce innovations in supply chains (Le Bail and Makowski 2004; Le Gal et al. 2008). Some of

275 these models have been adopted as tools for collective training and scenario design (Souchère et al.
276 2010). Such models may be useful for discussing global scenarios of agricultural innovation.

277 Most of this research has been carried out at the farm and regional scales. However, information
278 about farmers' practices is required at a larger scale to address global agricultural issues. For
279 instance, although knowledge of land-use categories (forests, grasslands, crops) may be sufficient for
280 the assessment of carbon sequestration, an in-depth knowledge of farmers' practices (fertilization
281 rates and dates, grazing practices or soil tillage) may be required for the accurate estimation of
282 greenhouse gas emissions at large scale (Stehfest and Bouwman 2006). Remote-sensing and large-
283 scale surveys are useful for describing current land use and farmers' practices (Mueller et al. 2012;
284 Ramankutty et al. 2008). (Mignolet et al. 2004) used such surveys to assess changes in cropping
285 patterns in the Seine basin in France (95 000 km²) over a 30-year period, to assess the link between
286 cropping systems and the nitrate content of the river water. They showed a gradual crop
287 specialization in this area (Le Ber et al. 2006). However, it would be difficult to apply their protocol at
288 a large scale. Expert knowledge may help to characterize cropping practices (Leenhardt et al. 2010;
289 Sacks et al. 2010). The gathering of data on farmers' practices over large scales remains, however, a
290 major challenge.

291

292

293 **4. Methods for addressing global issues in agronomy**

294 In this section, we present and discuss various methods for addressing global issues in agronomy.

295 Their objectives, advantages and disadvantages are summarized in Table 2.

296 **4.1. Experiments**

297 Experimentation is probably still the most popular method used by agronomists. Experiments form
298 the foundations of most of the knowledge accumulated to date in agronomy (see Section 2.1).
299 Experimental results may help to formulate general laws concerning the function of agroecosystems
300 at global scale, but the definition of general laws from local experiments is not straightforward. In
301 the past, too many agronomic experiments were conducted considering agroecosystems as a black
302 box, without measuring internal variables. As a result, it was not possible to “understand the reasons
303 behind” the observed responses (Garside and Bell 2011), and to discuss the validity of conclusions
304 derived from observations.

305 Fortunately, agronomic experiments are increasingly making use of instrumentation, which is an
306 advantage for studies of global issues as it allows agronomists to explore a wide range of conditions.
307 Most of the experiments are carried out at field stations, but a growing number are carried out on
308 real farms (Tueche and Hauser 2011; Kiba et al. 2012; Bertomeu 2012; Piepho et al. 2011). Some
309 experimental studies are also based on farmers’ practices, and make use of the diversity of these
310 practices to develop a heuristic design, without experimental treatment (Delmotte et al. 2011). This
311 approach takes into account the diversity of the farming conditions, which is absolutely essential for
312 addressing global issues as the results obtained at field stations may not be consistent with those
313 obtained on real farms. This may facilitate the prediction of agronomic results in areas in which few
314 factorial experiments have been carried out.

315 Experimental results are of critical importance for global agronomy. In particular, cropping system
316 databases including experimental results may lead to general conclusions based on the findings of
317 large numbers of experiments, e.g. the Chinese database of (Hou et al. 2012). They may also help
318 researchers to define theoretical principles concerning the functioning of agroecosystems on the
319 basis of large numbers of scattered references, through comparative agronomy (Doré et al. 2011).

320 However, agronomic experiments currently suffer from the limited development of integrated
321 databases for addressing global issues. There are some databases in existence, e.g., based on public
322 statistics (e.g., FAOSTAT), but they include few data for cropping systems or experimental results.

323

324 ***4.2. Crop, global vegetation and land-use models***

325 Crop models can be used to explore the response of key agronomic and environmental variables,
326 (e.g. crop yield or N losses) to climate, cropping system variables or societal changes (see Section
327 3.1). An interesting feature of these models is that they account for the effect of a wide range of
328 agricultural practices (Brisson et al. 2003; Stockle et al. 2003). They can thus be used to represent
329 and optimize management decisions, and to assess the impact of these decisions on crop production
330 and environmental variables (Bergez et al. 2002). Some of these models can also be used to generate
331 and assess crop management options (Dogliotti et al. 2005).

332 Dynamic crop models are frequently used to study the effect of climate change on crop yields
333 (Brisson and Levrault 2010). For instance, 90 papers presenting model-based simulations of climate
334 change effects on wheat yield were retrieved from the Web of Knowledge from 1991 to 2012 (Figure
335 3).

336 However, crop models are usually implemented at the field level, and their implementation at larger
337 scales is problematic. A major problem is obtaining the input data necessary to run the crop model:
338 physical input data (climate, soil characteristics and initial conditions) and data concerning crop
339 management. Several methods have been proposed for estimating input values at large scales,
340 including zoning, interpolation and remote sensing (Leenhardt et al. 2006), but the application of
341 these techniques is not always possible and may lead to uncertain input values.

342 On the contrary, Global dynamic vegetation models (GDVM) are now frequently used to assess the

343 regional or global impacts of climate changes on ecosystems. Unlike dynamic crop models, these
344 models generate an output that is regionally distributed over a regular grid and can thus be used to
345 draw maps at regional, national or continental scales. The ORCHIDEE model (Krinner et al. 2005) is an
346 example of a GDVM. This model calculates the energetic and hydrological budget of the soil and
347 vegetation continuum, together with the carbon and N cycles. Photosynthesis, phenology, the
348 allocation of carbon and nitrogen to the different organs, plant growth and mortality and the
349 decomposition of litter and soil organic matter are assessed with simple equations dependent on
350 various plant functional types. ORCHIDEE has been coupled to specific agricultural modules for
351 croplands (de Noblet-Ducoudré et al. 2004), to account for the characteristic phenology of such
352 anthropogenic ecosystems.

353 GDVM can be applied at local, regional or global scales over time scales extending from hours to
354 decades. The versatility of these models makes them very useful for regional assessments of the
355 impacts of climate change. However, GDVM have several limitations. Unlike dynamic crop models,
356 they generally simulate crop types (e.g., C3 and C4 crops), rather than crop species. These models do
357 not take into account agricultural practices and cannot be used to compare several cropping systems.
358 Moreover their high computation times make the implementation of classical uncertainty and
359 sensitivity techniques very difficult.

360 Species distribution models are frequently used to estimate the potential geographic distributions of
361 crop pests (Dupin et al. 2011). These estimations are based on local climatic conditions and pest
362 species requirements (e.g., optimal temperature for crop infection). Such models are frequently used
363 to draw maps of biological invasion risk at regional and global scales. These maps can be used to
364 assess future risks of yield and quality losses. However, the parameters of species distribution
365 models are difficult to estimate and the predictions of these models can be inaccurate (Dupin et al.
366 2011).

367 Finally, land-use optimization models based on linear programming (LP) can also be used to address
368 global issues. Linear programming has been recognized as an important tool for agricultural land-use
369 exploration since the 1980s (de Wit et al. 1988). LP models can be used to explore land-use
370 allocations optimizing agricultural, economic or environmental objectives at the farm regional and
371 continental levels (van Ittersum et al. 1998). A LP model includes an objective function (to be
372 minimized or maximized) and one or several constraints. In LP models developed for land-use
373 exploration, the objective function may represent an economic, agricultural or environmental
374 objective. LP models can be used to find an optimal solution (e.g. an optimal set of areas allocated to
375 the production activities maximizing an objective function and satisfying the constraints included in
376 the models). LP models are useful for exploring the effect of a change of objective and/or constraints
377 (e.g. a stronger constraint on the total amount of pesticides applied) on agricultural land use in a
378 region, country or continent. However, LP models have important limitations: they are static and
379 cannot easily be used to study land-use change over time. Moreover, LP models are also known to
380 generate nearly optimal solutions that can be very different from the optimal solution in terms of
381 land-use allocation but very similar in terms of objective function values (Makowski et al. 2000,
382 2001).

383

384 ***4.3. Yield gap analysis***

385 Yield gap analysis is a key method for addressing future food security issues at the global scale. A
386 yield gap is defined as the difference between the potential yield value and the yield actually
387 obtained by the farmer (Lobell et al. 2009). Yield gap values are useful for identifying geographic
388 areas in which yields could be increased, for determining the main factors limiting yield and defining
389 future research priorities (Casanova et al. 1999; Doré et al. 2008; Licker et al. 2010; Neumann et al.
390 2010; Prost et al. 2008). An analysis of yield gaps can thus help agronomists to determine where and

391 how crop productivity might be increased, if necessary. Yield gap analysis comprises two main steps:
392 yield gap estimation and the identification of factors explaining yield gap variability. Many studies
393 have focused on calculating and analyzing yield gaps, but several methodological problems are
394 encountered in attempts to apply this analysis at the global scale.

395 Four approaches have been proposed for estimating potential yields: i) crop model simulations
396 (Brisson et al. 2010), ii) field experiments and yield contests (Lobell et al. 2009), iii) farmers'
397 maximum yields (Lobell et al. 2009), iv) estimation from global crop datasets including yield values
398 and climatic variables (Licker et al. 2010; Monfreda et al. 2008; Mueller et al. 2012). Crop model
399 simulations are probably the most widely used (Lobell et al. 2009), but their implementation at the
400 global scale is problematic. Crop models require a large number of input variables related to climate,
401 soil characteristics and farmers' practices, and these variables are difficult to assess for large
402 numbers of sites. In addition, scaling up the results of crop model simulations to derive potential
403 yield estimates at the global scale is not straightforward. The maximum yields obtained by farmers
404 and local experiments can be used to estimate potential yield locally, but this approach cannot be
405 used directly at the global scale. In addition, the first two approaches cannot be used alone to
406 calculate yield gaps: they require a separate source of information concerning the actual yields
407 achieved by farmers.

408 Global crop yield databases can be used to estimate both potential yields and yield gaps at the global
409 scale (Licker et al. 2010). This approach is powerful and offers new perspectives for the analysis of
410 yield gaps at the global scale. However, the proposed technique for potential yield estimation
411 requires the categorization of climatic variables into a small number of categories and the number of
412 data in each category must exceed a certain minimum, for the calculation of yield percentiles. The
413 proposed method could be extended to the estimation of potential yields and yield gaps from global
414 crop datasets by means of quantile regression (Makowski et al., 2007). However, Figure 6 shows that
415 the yield values estimated by these techniques are sensitive to the selected probability value. In this

416 figure, wheat yield gaps were computed from the global yield database used by Licker et al. (2010).
417 Potential yields were computed by quantile regression for several probabilities ranging from 0.90
418 (estimated potential yields correspond to the 90th percentiles of the yield data) to 0.995 (estimated
419 potential yields correspond to the 99.5th percentiles of the yield data). When the probability used for
420 computing potential yield was set equal to 0.90, the median yield gap over all wheat plots of the
421 database was equal to 2.44 t ha⁻¹ (Figure 6). The median yield gap was much higher when this
422 probability was set to a higher value; it reached 3.54 t ha⁻¹ when the probability was set equal to
423 0.95, and 4.9 t ha⁻¹ when the probability was set equal to 0.99 (Figure 6). These results show that the
424 conclusions of a yield gap analysis can be highly sensitive to the procedure used to estimate potential
425 yields.

426 Other issues are the identification and ranking of limiting factors explaining yield gaps (Prost et al.
427 2008), the risk of confounding effects (i.e., the confusing roles of different variables due to
428 correlations, Bakker et al. 2005), and the dynamic changes in yield gaps over time (Laborte et al.
429 2012). Yield gap may vary over time due to the effect of climate change on potential yields and
430 changes in farmers' yields. Figure 3 shows the changes in farmers' wheat yields since the 1960s in
431 France and Spain. These two countries display different patterns of yield trends and yield variability.
432 In France, wheat yields reached a plateau in the mid-1990s. No such plateau has yet been reached in
433 Spain, but the yield percentiles presented in Figure 3 show that between-year yield variability has
434 increased in Spain since the 1980s and that yield values remain lower in Spain than in France. Several
435 explanations relating to climate, input use and farmers' learning curves have recently been discussed
436 as ways of interpreting farmers' yield dynamics (Brisson et al. 2010; Laborte et al. 2012). However, the
437 interpretation of farmers' yield dynamics remains a challenge, especially due to the high uncertainty
438 in the estimated yield trends. This high uncertainty is illustrated in Figure 7 where the standard
439 deviations of the estimated values of wheat yield yearly increase rates are shown for the 15 most

440 important wheat producers in 2010 (FAOSTAT); standard deviations are often close to and even
441 sometimes higher than the estimated values (Figure 7).

442

443 **4.4. Meta-analysis**

444 Meta-analysis could become a key method for determining general laws about the way in which
445 agroecosystems work. Meta-analysis is a quantitative systematic review of the literature, with the
446 application of a statistical treatment to the cumulative dataset. Most meta-analyses carried out to
447 date have been performed in medical science (Borenstein et al. 2009). This approach has been
448 applied, albeit less systematically, in other areas, such as ecology (Cardinale et al. 2006), and has
449 sometimes been applied in animal science (Sauvant et al. 2008) and plant pathology (Rosenberg et al.
450 2004).

451 The meta-analysis framework provides an interesting alternative to dynamic crop models, because
452 these models include several sources of uncertainty and their predictions are not always reliable
453 (Barbottin et al. 2008; Makowski et al. 2009). When a large body of scientific data is available, meta-
454 analysis appears to be a promising approach for assessing the agronomic and environmental
455 performances of agricultural practices at the global scale. For example, meta-analysis could be used
456 to assess the effect of a decrease in nitrogen application on N₂O emission at the global scale, based
457 on an analysis of an experimental dataset on N₂O emissions around the world. Meta-analysis can also
458 be used to study the global consequence of a change in cropping systems, such as the effects of
459 organic cropping systems on crop yields and food production (de Ponti et al. 2012).

460 Meta-analysis is a powerful tool, but its value may be greatly decreased by the use of inappropriate
461 techniques. Philibert *et al.* (2012) recently analyzed the quality of 73 meta-analyses carried out in
462 agronomy. They found that the quality of meta-analyses was generally lower in agronomy than in

463 medical science. Based on this quality assessment, the following recommendations were formulated:
464 i) the procedure used to select papers from scientific databases should be explained, ii) individual
465 data should be weighted according to their level of precision when possible, iii) the heterogeneity of
466 data should be analyzed with random-effect models, iv) sensitivity analysis should be carried out and
467 v) the possibility of publication bias should be investigated.

468

469 **5. Conclusion**

470 The growth of the human population and increasing concerns about the global impact of agriculture
471 are likely to lead to major changes in agronomic research in the next decade. As shown here,
472 agricultural scientists will tend to study new topics (e.g. food security, global impact of agriculture
473 activities on climate change and biodiversity) and to deal with new scales and new objectives.
474 Agronomists have traditionally worked at the field scale and, to a lesser extent, at the farm and
475 regional scales, but they are not yet used to working at the global scale.

476 Agronomists have developed a large range of methods and tools that may be of interest for
477 addressing global issues. However, this toolbox is not entirely suitable for application to global issues.
478 Most experiments and dynamic crop models are currently adapted to local issues (e.g., fertilization
479 management, local yield predictions) and their outputs cannot be easily be scaled up. Other
480 methods, such as global vegetation models, land-use models, and meta-analysis are likely to become
481 increasingly widespread in the future. They will allow to assess the effects of cropping practices at a
482 large scale and to study the impact of various agricultural activities on food security and the
483 environment. However, global agronomy will face the difficult task of drawing up general, global laws
484 about the way in which agroecosystems work.

485 Agronomists have a good knowledge of farmers' practices, and of the changes in and drivers of these
486 practices. They have shown that cropping practices result from many different determinants that
487 could be described through decision rules and models. Knowledge about farmers' practices may be
488 useful for the design of consistent scenarios of future, alternative cropping systems at the global
489 scale. Large databases on cropping systems would facilitate the design of such scenarios, but we still
490 lack reliable databases concerning farmers' practices (e.g. land use, fertilization, irrigation, sowing
491 dates). The situation is similar for the ecosystem services of agricultural activities, for which only a
492 few reference databases exist.

493

494

496 **Table 1: How global issues raise new scientific questions for agronomy, concerning nutrient management**
 497 **and global food security, for example**

	Issue 1: Nutrient management		Issue 2: Food security	
Scale	Field, catchment	Global	Field, landscape	Global
Examples of research topics	Assessing the effects of soil, climate and crop management on nutrient dynamics. Assessing the effects of landscape characteristics on nutrient flows	Identifying and assessing the different drivers of global nutrient use. Assessing the opportunities for nutrient recycling	Assessing the effects of crop management and landscape characteristics on crop yield.	Understanding global farming adaptation to climate change. Scaling up results from field-scale yield-gap analysis. Identifying which levers can be used and which should not be used to increase crop production in a range of situations.
Examples of	Managing nutrients to	Limiting global use of fossil P and	Assessing and improving field-	Assessing the global yield-gap of

objectives	maximize field crop production and to minimize environmental losses. Designing landscapes that minimize environmental losses.	reactive N.	scale farming system productivity. Assessing the role of the different limiting factors (yield-gap analysis at field scale).	different farming systems under scenarios of climate change and resource scarcity and paving the way for regional, continental and global solutions.
Methods	Field experiments, crop and catchment modeling	Global-scale modeling, database management.	Field experiments, crop modeling.	Global and regional scale crop modeling, meta-analysis, yield-gap analysis.
Output	Decision support tools.	Scenario assessment.	Decision support tools.	Scenario assessment.

498

499

500

501 Table 2. Objectives, advantages and disadvantages of methods for addressing global issues in
 502 agronomy

503

Method	Objective	Advantage	Disadvantage
Experiments	Understanding how agroecosystems work	Account for the variability of climate, soil and farming conditions	Future events (e.g. climate change) cannot easily be accounted for; data gathering and data analysis can be difficult
Dynamic crop models	Simulating effects of climate, soil, and management variables on crop production and environment	Account for a wide range of climate, soil and farming conditions	Not easily applied at large scales due to the problem of input estimation
Global dynamic vegetation models	Simulating soil, plant, and climate characteristics at regional and/or global scale	Can be applied at local, regional or global scales for time scales extending from hours to decades	Do not use a precise description of cropping systems
Land-use optimization	Optimizing land use	Can be applied at farm, regional and	May generate a wide range of land-use

models		continental scales. Take various objectives and constraints into account	allocations with similar performances
Species distribution models	Predicting the geographic distribution of pests	Take into account local climatic conditions and pest requirements	Parameter estimation can be difficult
Yield-gap analysis	Estimating yield gaps, and ranking of yield-limiting factors	Useful: <ul style="list-style-type: none"> - To identify the geographic areas in which yields could be increased, - To determine the main factors limiting yield, - To define future research priorities 	Require estimation of potential yields Ranking of limiting factors may be highly uncertain
Meta-analysis	Drawing up of general	Assessment of	Not relevant when only

	laws on how agroecosystems work based on the statistical treatment of a database derived from literature review	agronomic and environmental performances of agricultural practices at large scales	a few papers are available for the topic of interest. Its value may be greatly decreased by the use of inappropriate techniques
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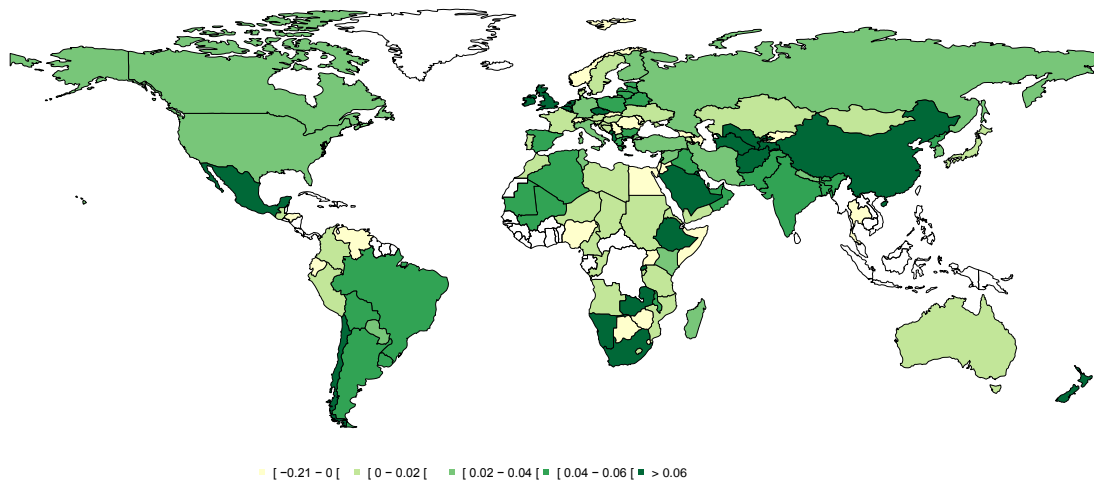
506 Figure 1. The global impact of agriculture has recently become a major research topic, stressed by
507 the rapid growth of the world population. The total population in Malaysia has increased by 256
508 percent during the last 50 years. In the Kuala Lumpur region, the population had tripled from its 1980
509 level.



510

511

512 Figure 2. Map showing values of yearly increase rate of wheat yield in 2010 ($\text{t ha}^{-1} \text{ year}^{-1}$). Wheat
513 yield increase rates were estimated for different countries from FAOSTAT wheat yield time series
514 using dynamic linear statistical models. For wheat in 2010, yearly increase rates range from negative
515 values (indicating yield decrease, in light yellow) to values higher than $+0.06 \text{ t ha}^{-1} \text{ year}^{-1}$ (dark green).
516 Yearly increase rate of crop yield is a key-parameter in foresight studies on food security.

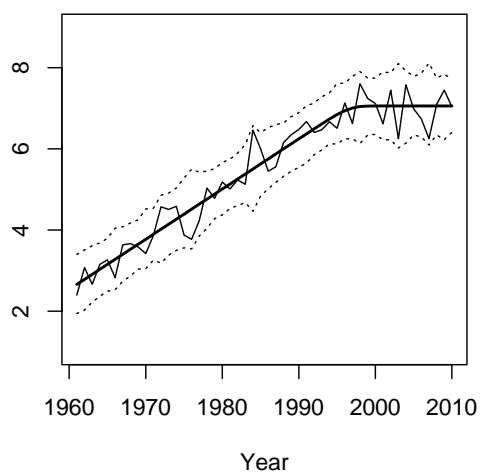


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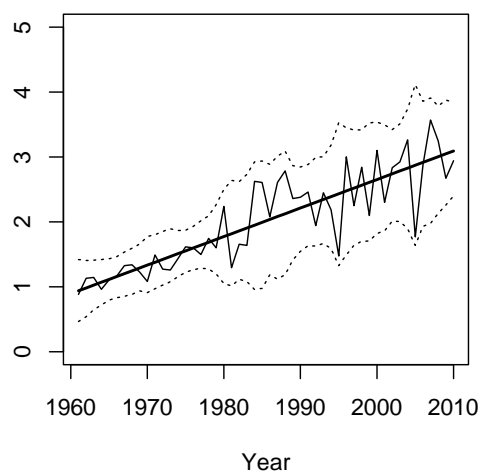
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519 Figure 3. Yield data (thin lines), fitted trends (thick lines), and 5 and 95% yield percentiles (dotted
520 lines) in France and Spain. Data are from FAOSTAT. Fitted trends and percentiles were estimated with
521 stochastic volatility statistical models (Meyer and Yu 2000). Yield percentiles indicate the level of
522 between-year yield variability and show that the yield variability has increased since 1980 in Spain.

Yield in France (t ha-1)



Yield in Spain (t ha-1)

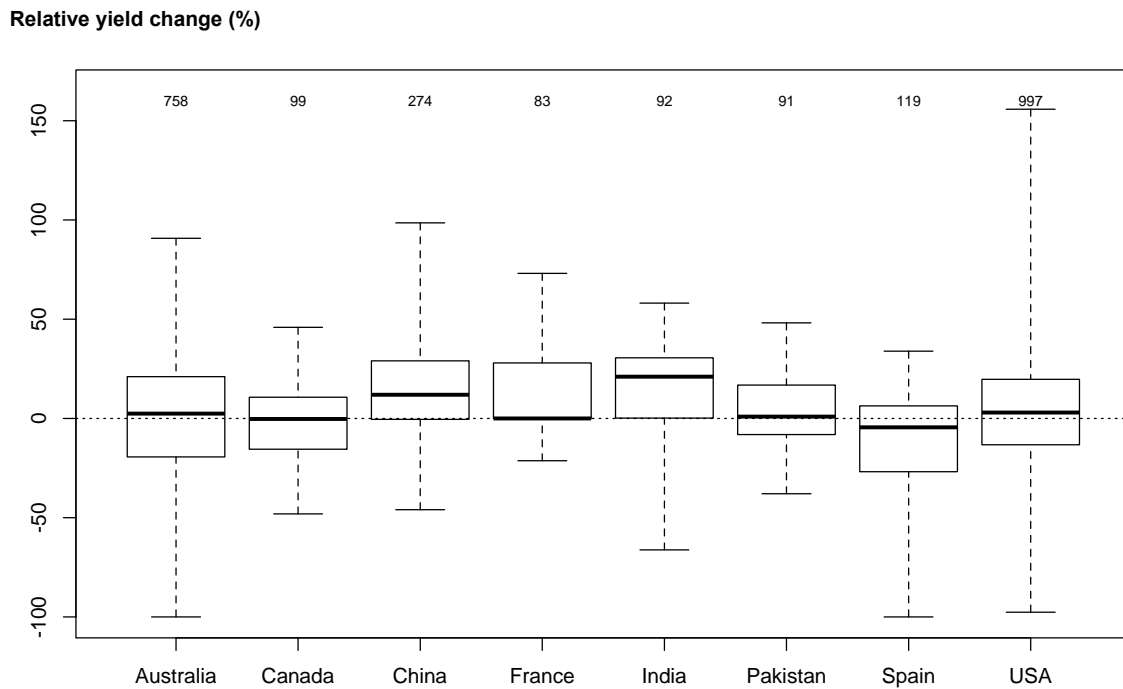


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525

526 Figure 4. Distributions of relative change (%) in wheat yield due to future climate change. Yield
 527 changes were computed from simulated data reported in 90 published papers for different countries.
 528 Relative yield change was defined by $RCY = 100 * (\text{future average yield} - \text{baseline average yield}) /$
 529 $\text{baseline average yield}$, where “baseline average yield” and “future average yield” correspond to yield
 530 values simulated by crop models and averaged over years for both baseline and future climatic
 531 scenarios. Each boxplot indicates the minimum, 1st quartile, median, 3rd quartile, and maximum of
 532 the RCY values available for each country (the numbers of available RCY values are given at the tops
 533 of the boxplots).



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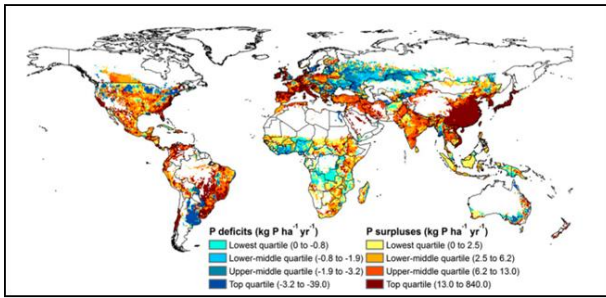
535

536 Figure 5. Using field-scale models simulating the effects of soil P budget on soil P availability (b) and
 537 the effects of soil P availability on crop production (c) to relate global soil P budgets (a) to global crop
 538 production (d). Step (d) needs further research works.

539

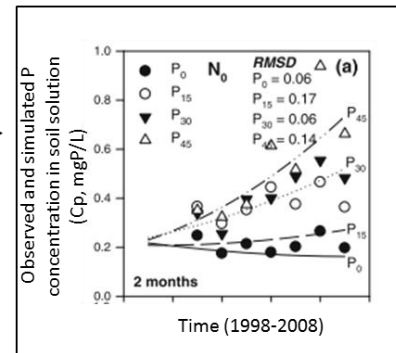
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(a) Global-scale map of soil P budget (50 km x 50 km)



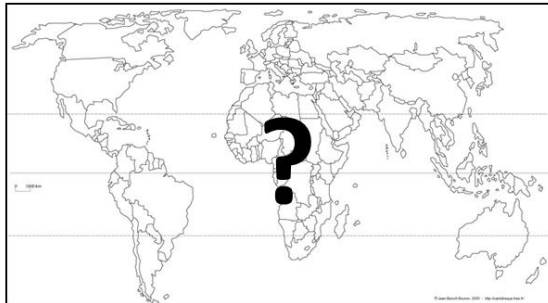
(MacDonald et al, 2011)

(b) Field-scale model relating soil P budget to soil P availability

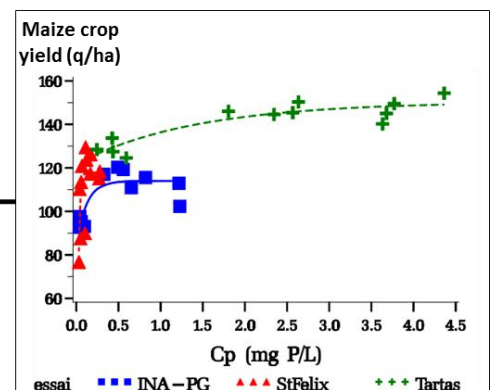


(Messiga et al, 2012)

(d) Global-scale map of crop production



(c) Field-scale model relating soil P availability to crop production



(Morel, 2002)

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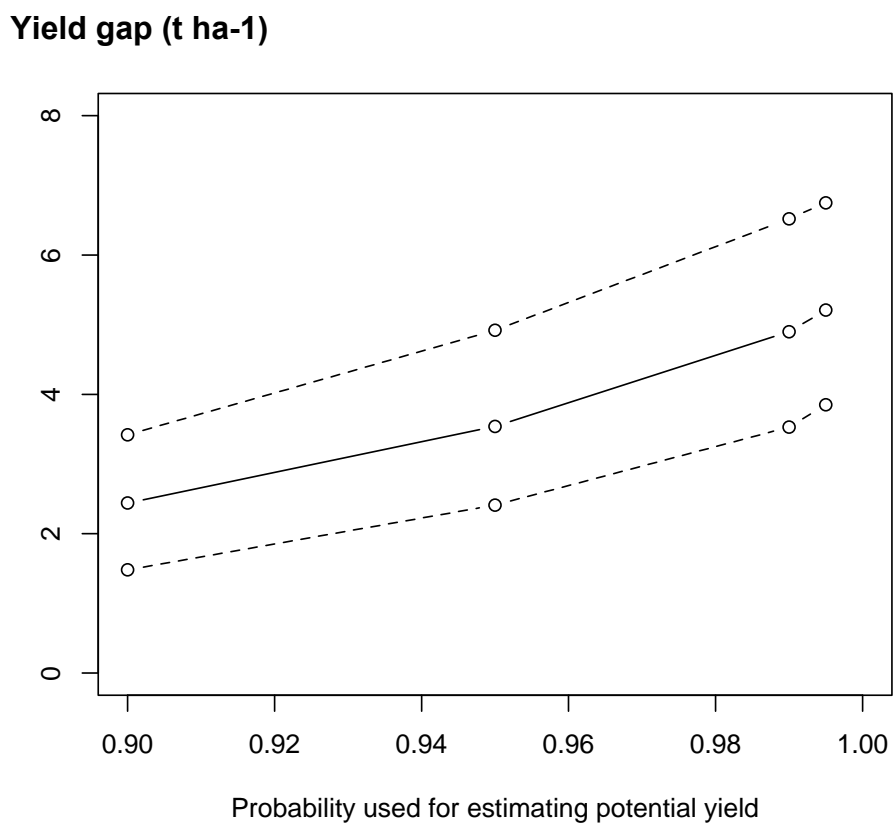
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548 Figure 6. Sensitivity of wheat yield gaps to the probability chosen for estimating potential yields. The
549 continuous line indicates the median yield gaps over all wheat plots included in a global database at
550 the world scale (database used by Licker et al., 2010). The dashed lines indicate the 1st and 3rd
551 quartiles of the yield gaps over all wheat plots.



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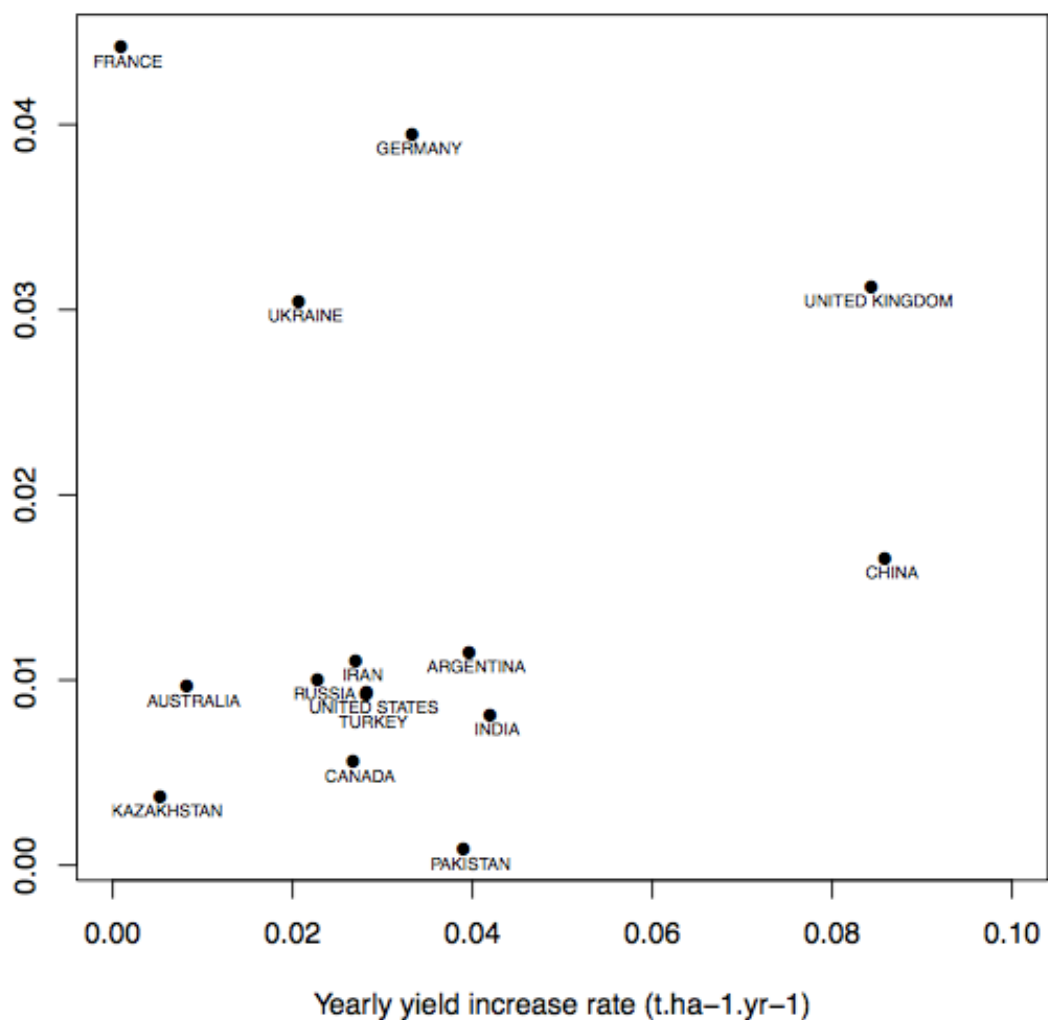
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556 Figure 7. Estimated yearly increase rates of wheat yield ($t\ ha^{-1}\ year^{-1}$) in 2010 and standard deviations
557 of the estimated values. Results were obtained for the 15 countries with the highest wheat
558 productions in 2010, from a statistical analysis of yield time series (FAOSTAT).

559

Standard deviation of yield increase rate ($t\ ha^{-1}\ year^{-1}$)



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