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Which decision support tools for the environmental management of nitrogen?

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Abstract – Which decision support tools should be developed to help agricultural stakeholders manage nitrogen in an environmentally friendly way? This paper presents the limitations of current decision support tools with respect to the implementation of a four-step quality spiral. PLAN: planning technical actions that satisfy both economic and environmental constraints. The priorities are to develop decision tools at the farm and the regional levels, and to estimate the indirect effects of nitrogen on the environment due to its interaction with pesticides. DO: implementation of technical actions. The design of decision support tools must integrate more information about the way in which farmers and their advisors will use the tools. CHECK: efficiency of the “PLAN/DO” steps must be evaluated on different scales. The priority is to propose and validate environmental indicators. ACT: definition of new priorities for the next loop. Research is required on diagnosis tools for tracing back the causes of environmental problems.

nitrogen / environmental management / environmental diagnosis / model decision tool / cropping system

Résumé – Quels outils d'aide à la décision pour le management environnemental de l'azote ? Quels nouveaux outils d'aide à la décision doivent être proposés en matière de gestion de l'azote pour aider les acteurs de l'agriculture à maîtriser au mieux les impacts environnementaux de leurs pratiques ? Cet article analyse les insuffisances des outils actuels autour d'une réflexion organisée selon les 4 étapes de la « boucle du management environnemental ». PLAN : planification des actes techniques en vue de concilier objectifs économiques et environnementaux. Il serait nécessaire de développer des outils d'aide à la décision aux niveaux de l'exploitation agricole et de la région. De plus, les outils actuels ne prennent pas en compte les conséquences environnementales de la gestion de l'azote sur les autres éléments de l'itinéraire technique. DO : mise en œuvre des actes techniques. Une meilleure appréhension de la diversité des usages et des contraintes des utilisateurs est indispensable pour proposer des outils pertinents et adaptables. CHECK : évaluation de l'efficacité environnementale du « PLAN/DO ». Elle repose sur l'utilisation d'indicateurs environnementaux dont la validation est trop rarement effectuée. ACT : définition des priorités d'action pour une nouvelle boucle. Elle nécessite la mise au point d'outils de diagnostic environnemental permettant d'identifier les techniques culturales à améliorer.

azote / management environnemental / diagnostic environnemental / outil d'aide à la décision / système de culture

1. INTRODUCTION

Agronomic practices are now a matter of public concern and have moved beyond solely the farmers' sphere. Transactions involving agricultural products are increasingly subject to specifications imposing traceability and production techniques, and the authorities forbid certain practices by means

of regulation, or encourage others by specific support. Farmers owe it to the citizens of their country and the consumers of their products to maintain transparency concerning their practices, guaranteeing that they produce safe foods by clean agriculture

This article does not deal with the means of ensuring food safety, but instead focuses on the means of guaranteeing

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clean agriculture, addressing the following question: “What are the new areas of research required specifically for the development of new decision-making tools, and particularly for the issue of nitrogen, such that agricultural stakeholders will have the means to guarantee to society that they control the environmental impact of their activity?”. Two major problems are immediately apparent:

- The diversity of agricultural conditions may result in the same practice having different effects in different places. Protection of the environment requires farming practices to be adjusted to field characteristics such as soil type, climate, cropping system, or crop N status. The imposition on all farms of regulations or specifications concerning production methods cannot, in itself, guarantee clean agriculture.
- Rapid changes in economic conditions force farmers to adapt their practices. However, the substitution of one crop for another in the rotation or an increase in the amount of fertiliser applied (associated, for example, with a market demand for a higher protein content in the harvest) may be detrimental to the farm's environmental balance sheet. The sustainability of cropping systems must be combined with flexibility.

In a rapidly changing context and in the face of diverse agricultural conditions, no ready-made solution, no all-purpose advice can ensure the guarantee that agriculture respects the environment. In this situation, the most effective way of controlling environmental pollution would be for each person involved, whether directly or indirectly, in advising or implementing farming practices to evaluate the environmental consequences of their past actions and modify their activity in consequence, in a spiral of continuous process improvement [59]. Such an approach, under the name of “Environmental Management”, is implemented in International Management Standards such as ISO 14000, which aims to guarantee that certified firms respect the environment [70].

The environmental management approach is classically described by the four steps of the « quality spiral of continuous process improvement » (Plan, Do, Check, Act; PDCA, Fig. 1):

- Plan: this step involves the planning of actions, taking into account their consequences for both production and the environment.
- Do: the second step is the carrying out of the planned actions.
- Check: in the third step, the efficacy of the plan is assessed, making it possible to modify it slightly or radically, as necessary.
- Act: in the last step, the results of the three previous steps are analysed and priorities are set for the next PDCA loop [51, 71].

For the agricultural stakeholders, this approach is not particularly original; they spontaneously use it on their farm or in their agro-industry for economic management. However, its use for controlling the environmental impact of agriculture is still rare, and is associated with various difficulties,

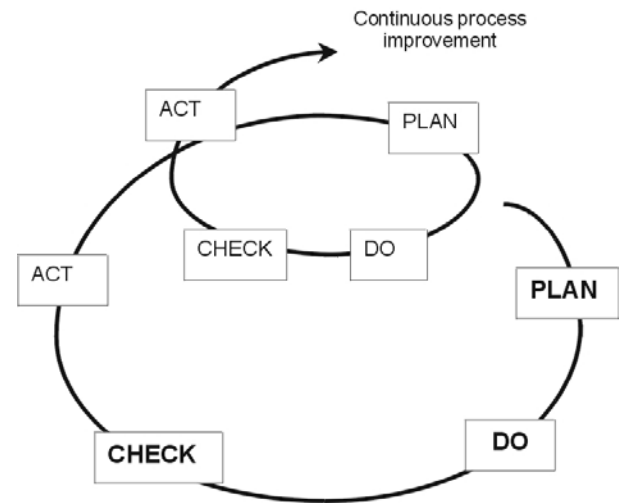


Figure 1. The quality spiral of environmental management.

some of which should be addressed by researchers. Here, we break this environmental management approach down into four steps to identify the research work that is needed for decision-making tools concerning nitrogen management. The aim is to provide society with a genuine guarantee that agriculture can control its environmental impact. For each step, examples will be used to present the main types of decision-making tools available, and their shortcomings. The examples are mostly from cropping systems including cereals, and are not intended to be exhaustive.

2. PLAN: TOOLS FOR NITROGEN FERTILISATION AND CROPPING SYSTEM MANAGEMENT

There has been a substantial amount of work to improve nitrogen fertilisation and cropping system management to reduce the leakage of nitrogen to the environment [29, 46, 65]. The most classical decision support tools are based on the use of in situ observations and measurements to adjust interventions to the characteristics of the farmers' fields, and thereby prevent underuse, the impairment of production, and overuse, harmful to the environment (Sect. 2.1). Most recently, tools have been developed making use of progress with models of the utilisation of nitrogen by the plant and the flow to the environment (Sect. 2.2). However, there are still no tools which take into account all the environmental consequences of nitrogen management techniques (Sect. 2.3).

2.1. Use of in situ observations and measurements for adjusting farmers' interventions to field characteristics

For many years, different types of measurement have been proposed to facilitate the adjustment of nitrogen fertilisation to field characteristics (see the review by Smith et al. [65]).

For example, soil mineral nitrogen at sowing or at the end of winter, and soil organic nitrogen availability indices can be used to calculate nitrogen fertiliser doses; residual soil mineral nitrogen at harvest has been proposed as an index for evaluating the usefulness of sowing a cover crop to prevent excessive nitrate leaching during the winter. Some plant variables, such as nitrate concentration in stem base extract [33] and chlorophyll content in the upper leaves [69, 73], can also be used to determine the optimal period for nitrogen application to the crop. A method has recently been suggested for determining the date of nitrogen application on cereals, based on the visual detection of a change in colour between a double-density strip and the rest of the field sown at single density [43]; this method increases fertiliser recovery and minimises nitrogen losses to the environment. Rapid advances in remote sensing are currently providing farmers with more information on the nitrogen status of crops. Thus, nitrogen fertiliser management could be improved by coupling crop models with spectral reflectance measurements, according to the aims of Precision Agriculture [4, 9].

The qualities of the tools that are necessary for determining the date of application of nitrogen fertiliser (specificity, sensitivity, robustness) were described in a recent review [51]. However, to date, plant nitrogen status indicators have been proposed only as a means of ensuring non-limiting nitrogen nutrition throughout the crop cycle. Yet, periods of nitrogen deficiency are not always detrimental to yield [30]. Such indicators cannot be used directly to develop strategies of nitrogen fertilisation allowing short periods of nitrogen deficiency. Due to this limitation, it is generally not possible to use these indicators in organic agriculture to guide the application of labile organic fertiliser because, in this type of farming system, the cost of organic nitrogen fertiliser is so high that it is rarely profitable to satisfy crop nitrogen requirements fully [17]. In the future, it will be necessary to develop indicators compatible with suboptimal nitrogen nutrition of the crop during part of the cycle.

2.2. Model-based decision support tools for nitrogen management

Biophysical models are increasingly being used to improve cropping techniques and cropping systems [8, 10]. This trend results from a combination of the arrival at maturity of mechanistic models designed by crop physiologists, soil scientists and micrometeorologists, and growing awareness of the inadequacies of field experiments for responding to the new questions of sustainable agriculture. The models simulate environmental outcomes that are difficult to measure (e.g. gaseous emissions in the atmosphere; [24]). They also enable researchers to speculate on the long-term consequences of changes in agricultural practices. Finally, they make it possible to identify very rapidly the adaptations required to enable cropping systems to respond to changes in the economic or regulatory context [59].

2.2.1. Use of models for nitrogen management at the field level

In the domain of nitrogen management, few studies have used models either to compare the long-term impact of different cropping or farming systems [36, 40] or to analyse the consequences of the management of catch crops on nitrate leaching [20]. However, most of the applications based on models deal with the optimisation of nitrogen fertilisation. Recent agronomic models include output variables assessing crop yield, product quality, farmers' income, and environmental impact. These models can therefore be used to optimise nitrogen fertilisation, establishing compromises between the various conflicting objectives. For example, the model of Makowski et al. [47, 48] was used to calculate, for different crops, optimal nitrogen fertiliser rates for maximising farmers' income, and to analyse the consequences of applying the calculated fertiliser rates on crop production and residual mineral nitrogen in the soil at harvest. Table I gives examples of results obtained with this model for winter wheat. This type of model allows the farmer or his advisor to adapt the dose of fertiliser according to its cost, the price of the product harvested or environmental regulations. It can also be used by the authorities to compare the economic and environmental consequences of various possible regulations: they can then choose those which most effectively attain the desired objectives. These models provide the stakeholders with an objective basis for analysing the consequences of compromises considered during negotiations (see [5] and [48] for details).

The use of dynamic crop models for fertiliser management could only progress as the number of input variables – inherently large for these models – was reduced, without affecting their predictive value (see SUNDIAL [66] and AZODYN

Table I. Values of optimal nitrogen dose, yield, grain protein content and residual soil mineral nitrogen at harvest obtained for four economic scenarios, for a winter wheat field with 50 kg-ha⁻¹ of soil mineral nitrogen at the end of winter. Optimal nitrogen doses were calculated by maximising farmers' gross margin for the reference scenario and for scenarios 1, 2 and 4. (Source: Model Makowski et al. [47].)

Economic scenarios	Change in the optimal N rate	Change in yield	Change in grain protein	Change in residual nitrogen
	kg-ha ⁻¹	Mg-ha ⁻¹	%	kg-ha ⁻¹
1	- 20	- 0.1	- 0.29	- 4.3
2	+ 30	+ 0.096	+ 0.41	+ 7.0
3	- 40	- 0.26	- 0.58	- 8.3
4	- 10	- 0.048	- 0.14	- 2.2

Reference scenario: Grain price = 107 euros-Mg⁻¹, fertiliser price = 0.45 euros-kg⁻¹, grain yield = 9.48 t-ha⁻¹, fertiliser rate = 210 kgN-ha⁻¹.

Scenario 1: Grain price = 107 euros-Mg⁻¹, fertiliser price = 0.70 euros-kg⁻¹.

Scenario 2: Higher grain price if grain protein content exceeds 10.5% (+ 1.5 euros-Mg⁻¹ for each additional 0.5% of grain protein content), fertiliser price = 0.45 euros-kg⁻¹.

Scenario 3: The applied N rate is the optimal N rate obtained for the reference scenario, reduced by 20%.

Scenario 4: Excess of nitrogen at the farm level is penalised by 0.23 euros-kg⁻¹ (farm surface fixed to 100 ha), grain price = 107 euros-Mg⁻¹, fertiliser price = 0.45 euros-kg⁻¹.

[30, 32]). One important advantage of the dynamic models is that they can help to determine the optimal dates and optimal splitting of fertiliser applications [32, 68]. They also simulate more accurately nitrogen losses linked to environmental conditions in the first few days after fertiliser application, although further progress is required before the factors determining the gaseous losses following fertiliser application can be taken into account in a straightforward way [23, 44]. For example, AZODYN simulates the fate of applied fertiliser according to the crop growth rate at the time of application: a higher crop growth rate at the date of fertiliser application is associated with higher levels of fertiliser recovery and lower gaseous losses [39, 43]. As an example, in Table II, five fertiliser splitting strategies (with the same total amount of fertiliser applied) are compared for two wheat crops differing in the dynamics of available N in the soil during the season, but not in the total soil nitrogen supply. According to the simulations, if the objective is to maximise yield and grain protein content, strategies 3 and 4 are optimal in field 1 and strategy 5 is optimal in field 2. As the model simulates the consequences of fertilisation strategies for yield, grain protein content, mineral N in the soil at harvest and gaseous losses, the final choice of the best strategy from a larger number of simulations could be based on multicriteria analysis [45].

2.2.2. Use of models for nitrogen management at the farm or catchment levels

Although the use of decision support models for decisions concerning single fields or plots is becoming more widespread, there are few tools available for designing innovative means to manage nitrogen in areas on a larger scale. Many environmental problems can only be resolved by spatial organisation of cropping systems. For example, at the level of a catchment basin, it is possible to limit risks of water pollution by co-ordinating cropping systems: those which cause little

pollution (for example, permanent grazing or a low input system) would compensate for others for which it is difficult or expensive to avoid the leaching of nitrate. Thus, the overall risk could be maintained at an acceptable level for all stakeholders [55]. The development of a genuine support for decision-making for the spatial management of nitrogen requires further research with two types of tool:

- Tools simulating the consequences of the spatial distribution of cropping systems and organic input on the nitrogen flux [40, 55]. These tools should consider transfers between fields by runoff, sub-surface flows and ammoniac volatilisation and deposition. Such tools could be used as a support in negotiations between the various stakeholders affected by the management of an agricultural space. As Rossing et al. pointed out [59], the simulator enables each stakeholder to test the consequences of their personal preference on the zone considered, which greatly facilitates the negotiations: simulation tools allow clear distinction between a body of biological and technical knowledge which the stakeholders can all accept, and the objectives and constraints of each preference causing the disagreement.
- Tools analysing, on both the farm and regional scale, the consequences of agricultural product prices and regulations on farmers' choices of cropping system (acreage and location of each crop in the farm, rotations, management of each crop), and the environmental consequences of these choices [58]. Such tools are at the interface of agronomy and microeconomics, and are designed to be used by the authorities to help them establish agricultural policy and legislation that reconciles the best interests of the farmers and the environment. They could also be used by agro-industrial companies for determining prices and contracts favouring both, ensuring the supply of products of suitable quality and the control of nitrogen pollution in their supply basin.

Table II. Comparison of five N fertilisation strategies for two fields differing in the preceding crop and in the amount of mineral N in the soil at the end of winter (same physical soil characteristics; same crop biomass at the end of winter). Consequences on yield ($\text{Mg}\cdot\text{ha}^{-1}$), grain protein content (GPC, %), soil mineral N at harvest ($\text{kg}\cdot\text{ha}^{-1}$), and gaseous N losses ($\text{kg}\cdot\text{ha}^{-1}$). Values of Mr indicate net mineralisation of crop residues.

	Strategy 1 (classical splitting)		Strategy 2 (high 3rd rate)		Strategy 3 (no 1st application)		Strategy 4 (no 1st appl.; earlier 2nd and 3rd rates)		Strategy 5 (no 1st appl.; later 2nd and 3rd rates)	
	15/2	60	15/2	60	15/2	0	15/2	0	15/2	0
	20/3	120	20/3	80	20/3	160	15/3	120	1/04	140
	8/5	40	8/5	80	8/5	60	1/5	100	15/5	80
Field 1: End of winter mineral N = 30 $\text{kg}\cdot\text{ha}^{-1}$; preceding crop= faba bean (Mr = 30)										
Yield	9.5		8.7		9.8		9.7		8.6	
GPC	10.7		11.9		11.7		11.3		14.2	
Harvest N_{\min}	22		22		22		22		22	
Gaseous losses from fertiliser	51		38		31		24		~ 0	
Field 2: End of winter mineral N = 80 $\text{kg}\cdot\text{ha}^{-1}$; preceding crop= wheat (Mr = -20)										
Yield	9.8		9.7		9.8		9.8		9.8	
GPC	9.9		10.4		10.5		10.9		12.0	
Harvest N_{\min}	21		21		21		21		21	
Gaseous losses from fertiliser	51		38		31		17		~ 0	

2.2.3. Methodological problems of the use of models for decision support

The use of models for decision support poses several methodological problems that have not yet been fully resolved. One problem is the estimation of model parameters. Methods for estimating the parameters of relatively simple models, such as the fertilisation model of Makowski et al. [47], are now well established. This makes it possible for development engineers to use this type of model. In contrast, parameter estimation remains a difficult task for dynamic models, due to the large number of parameters involved [72]. In all cases, the quality of parameter estimates depends heavily on the quality of the database. The cost of acquiring the data required for parameter estimation is an important criterion that should be taken into account in the conception of models for use in decision support.

Another major problem is the evaluation of model performance. Model evaluation is essential for selection of the appropriate model for a given problem and for quantification of the consequences of incorrect decisions. Classical statistical techniques for model evaluation, which can be used to evaluate the quality of adjustment of models to data [14, 53] or to evaluate the quality of predictions based on models [21, 71], are useful but insufficient. We need to be able to evaluate the ability of the model to identify the best strategy for a given set of objectives and constraints. As an example, the statistical method developed by Antoniadou and Wallach [2] can be used to evaluate the fertiliser recommendations derived from models. No equivalent method has been developed for the evaluation of fertiliser splitting strategies.

2.3. The indirect effects of nitrogen management on the environment

The only environmental impact of nitrogen considered in this article until now concerns the pollution of water and air by uncontrolled nitrogen flows. In part due to the specialisation of research workers, indirect effects of nitrogen management on other environmental factors, particularly pollution by pesticides, have been little studied.

Yet many techniques that modify nitrogen management can have major effects on pesticide use. Non-limiting nitrogen nutrition conditions favour the development of many fungal diseases, leading to higher losses of yield or the application of larger amounts of fungicide [41, 67]. Soil tillage has consequences both for crop residue decomposition and for the dissemination and survival of weed seeds and disease inocula (see, for example, [15]). Some nitrate catch crops may increase the multiplication of inoculum (e.g. take-all on gramineous catch crops [28]), whereas *Brassica* catch crops may have a biofumigation effect on the soil during their decomposition [35]. Improvements in our understanding of these interactions and quantification of their effects are required if we are to coordinate the control of nitrogen losses and integrated crop protection against weeds, pests and diseases. For example, Dejoux et al. [18] proposed in France to use early sown (around 1 month before the recommended

dates) oil seed rape as a nitrate catch crop in plots that received large quantities of sludge or slurry. The early sowing and the absorption of large amounts of nitrogen were associated with a very high leaf area index in autumn that rendered the crop very competitive against weeds and less susceptible to slug damage. Applications of herbicides and molluscicides may therefore be reduced, without reducing the economic performance of the crop [18].

Finally, none of the available soil/crop models take into account the consequences of nitrogen management on all the processes affected, directly or indirectly. For example, models used for fertilisation management, described above, do not simulate the effects of this technique on fungal disease or weeds. This drawback clearly limits the domain of application of these models to agricultural situations in which the factors limiting growth and yield are well controlled (mainly conventional intensive agriculture). However, the consideration of these effects is necessary for the environment-friendly management of fertilisation in organic and integrated farming systems [17].

3. DO: THE USE OF DECISION SUPPORT TOOLS BY FARMERS AND THEIR ADVISORS

The discrepancy between the representations on which researchers and engineers base their advice, and the manner in which farmers make their decisions has been shown in various studies [3, 13, 27, 34, 54]. As most of the available decision support tools (based on models and/or nitrogen status of the soil or the plant, see above) are constructed around the representations of researchers and engineers, this discrepancy results in underuse of the tools developed, leading to the persistence of environmentally damaging practices, even if solutions are known. Moreover, it has been shown that advisors also fail to use the tools as recommended by their designers [12, 22]. We suggest that it might be possible to increase the adequacy of tools designed by researchers in agronomy by taking into account more fully the constraints and objectives of farmers and their advisors concerning the use of such tools. Research studies on decision support tools for fertilisation have suggested various characteristics that tools should possess to ensure use by farmers and their advisors.

3.1. The use of decision support tools by farmers

It is widely accepted by agronomists that nitrogen input should be determined on the plot scale, according to the dynamics of mineral nitrogen in the soil and the requirements of the crop. Thus, the scale and time of data collection are determined by the scale of action (the plot) on the one hand, and the functioning of the agrosystem on the other. However, for farmers with limited amounts of time available for observation and operational activities, reasoning is on the scale not of the individual plot, but of all the plots sown with the same crop [3]. The variability within this group of plots is not considered in terms of crop functioning, but in terms of the changes that the farmer thinks it necessary to incorporate into

his “routine procedure” for a given task [11]. Observation is therefore guided by the identification of situations that the farmer considers to be outside the conditions of validity for this routine procedure [13]. For nitrogen fertiliser application, for example, research has shown that most farmers have the same kind of routine procedure, based on a mean rate of fertiliser application and several simple rules used for adjusting this rate as a function of cropping history and soil type and, in some cases, year [12]. On some atypical plots (such as those previously fertilised with organic manure, for example) for which the farmer finds that the “routine procedure” is inappropriate, more complex methods of fertilisation, such as those based on the measurement of the nitrogen status of the plant (see above), which require specific and time-consuming data collection for each plot, may be used [22]. Finally, as shown by Aubry et al. [3], to simplify the organisation of their work, farmers tend to apply fertiliser to all their plots on the same date, determining the date of application from the monitoring of only a few of the plots.

These results have various consequences for tool design. Firstly, tools should be designed such that monitoring can be planned in advance, with models based on information collected before peaks in workload. This can be achieved, as described by Meynard et al. [51], by coupling plant N status indicators with dynamic models: plant N status measurements are used to calibrate the model, which then simulates changes in plant N status. In this case, intervention is not directly triggered by measurement of the nitrogen nutrition status indicator, but the pattern of change of the indicator simulated by the model. Secondly, models that estimate the economic and environmental losses associated with the deviation of interventions from optimal dates should be developed to provide farmers with support to help them make rational decisions about work organisation and application dates. Thirdly, as farmers manage their crops using a routine procedure, it would be useful if decision support tools (i)

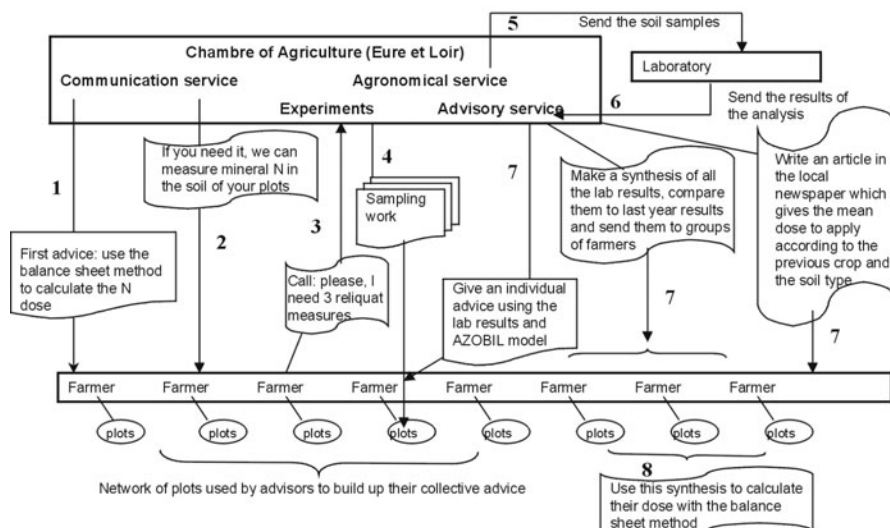
generated the “routine procedures” (simple rules applicable in most cases), (ii) provided the means of recognising situations in which the routine procedure is inappropriate, and (iii) supplied for these situations more appropriate, although more complicated, decision rules. This also has consequences for tool validation: in most cases, designers test their tools in typical situations, whereas these tools are generally used more extensively in unusual situations.

3.2. The use of decision support tools by advisors

The farmer is not the only user of decision support tools. Several stakeholders (agricultural advisors, crop consultants, fertiliser salesmen, etc.) may be involved in the analysis of a particular problem and the selection of an appropriate solution. Their relationship with decision support tools is different to that of the farmer. For example, a survey conducted by Emonet [22] in Lorraine (eastern France) among 30 advisors from various organisations showed that a given plant nitrogen status indicator, such as the “nitrate content of stem base extract”, may be used in different ways by different advisors, depending on their objectives. He identified 4 main uses:

- demonstrations “in the field” (tool to train farmers);
- analysis of trends for the year on a network of plots (tool to advise farmers);
- rationalisation of fertilisation in atypical situations (learning tool; typical use of the JUBIL method [33]);
- reference for evaluating by comparison the reliability of a new indicator (chlorophyll meter) reputed to be easier to use (reference tool).

Furthermore, studies that we are currently conducting to determine how information is collected by farmers or advisors for a given decision show that the decision-making process is distributive. Figure 2 shows the exchange of information between the advisory service and farmers in the



1 Different phases of the decision process

Figure 2. The distributive nature of decisions; example of the exchanges of information between the advisory service and the farmers in the determination of the N fertiliser rate for arable crops in Eure-et-Loir (France).

determination of the N fertiliser application rate for arable crops in a French region (Eure-et-Loir, in the Paris Basin). A large number of different people seem to be involved in deciding how much N should be applied: the communication department of the local advisory service, technicians in charge of experiments, advisors, laboratory technicians and farmers. The decision process extends over rather long periods of time due to its distributive nature. Last, but not least, advisors use networks of plots to generate collective advice, but may also give individual advice based on the farmer's own results. The various users of tools (in this example, the balance-sheet method and AZOBIL software [52, 57]) do not necessarily have the same means of action, do not necessarily work on the same scale and may use the tools at different times, with different demands in terms of response time of the indicator or of the model.

These observations suggest that tools should be developed that could be used pertinently on the scale of a regional network of plots, as this seems (at least in France) to be the most frequent use made of these tools by advisors. They also suggest that guidelines should be drawn up to support advisors in designing such networks. In addition, the distributive nature of the decision-making process makes it necessary to take into account the role of tools in the production and distribution of information. This role also determines the properties of the models and the nitrogen status indicators that should be included in the tools, thereby also determining the evaluation procedures required.

3.3. Maintenance of tools by advisors

Although the design of decision support tools should be based on an explicit definition of their mode of use, it is also necessary to integrate into these tools the constraints faced by advisors trying to maintain them. For example, it has been shown that any interpretation of nitrogen nutrition status based on the nitrate content of wheat stem base extract should take into account the plant variety [38]. Consequently, the adaptation to new varieties of the tools that use this plant nitrate content to determine fertilisation rates requires new experiments each year. A good decision support tool should be easy to adapt to changes in genetic material or cropping systems (few parameters involved and easy acquisition of the necessary data). The constraints involved in adapting the balance-sheet method to the diversity of conditions in France (reduction of the cost of model evaluation and re-estimation of local parameters) has led to modification of the equation used in this method [51]. The amount of nitrogen accumulated by an unfertilised crop and the coefficient of fertiliser recovery are now explicitly included in the equation because these two values are much easier for agronomists to measure in on-farm experiments during local adaptation and evaluation than are the analytical terms of the initial balance sheet (net mineralisation, nitrogen in the soil at harvest, etc.). Therefore, the cost of maintenance (number of people involved, number of experiments to be conducted, etc.) should be regarded as an important criterion in the design of decision support tools.

4. CHECK: THE TOOLS FOR THE ENVIRONMENTAL EVALUATION OF THE CROPPING SYSTEMS

“Evaluating the environmental impact of cropping systems” involves checking the efficacy of actions with respect to their environmental objectives. Are the environmental objectives attained? If not, why not? Evaluation is, above all, a method for improving the targeting of future actions. Therefore, such evaluation concerns all stakeholders involved in agriculture.

4.1. Various scales of environmental evaluation

At the level of the farm or the field, the farmer is the most concerned:

- After the harvest of the crop, the farmer reviews his practices and analyses the technical problems encountered. His aim is to classify situations with respect to environmental risks, in order to adapt the management of crop residues and the possible sowing of a nitrate catch crop. Beyond these tactical management decisions, the farmer can also identify techniques that pose problems, leading to a reassessment of the crop management strategies used [49].
- In the long term, farmers also need to estimate the risks associated with their practices. For example, in France, farmers will soon be subject to an annual environmental tax, which will be based on the cumulative excess of the nitrogen in the farm balance sheet during the previous year [1]. A strategy aiming at reducing excess nitrogen by depleting the soil organic matter, thereby minimising taxation in the short term, could have negative effects in the long term. The farmer therefore needs tools to enable him to understand the long-term agronomic consequences of short-term economic decisions.

On the scale of the region, agricultural advisors, local agricultural representatives and public decision-makers also need to evaluate cropping systems:

- Agricultural advisors need to identify, at the regional level, situations presenting an environmental risk. For example, the effective control of widespread pollution of water with nitrates, phosphates or pesticides requires collective action at the level of the catchment area. At this level, advisors need methods which enable them to recognise and to rank risks and to assess the areas concerned, so as to target advice more effectively [63].
- Local agricultural representatives, agro-industry and authorities must take on board the potential consequences of the actions they perform or support [19]. For these stakeholders, evaluation of the environmental impact of cropping systems, by means of the scenarios it makes it possible to construct, is an essential element in dialogue, negotiation, and optimisation of the use of financial resources.

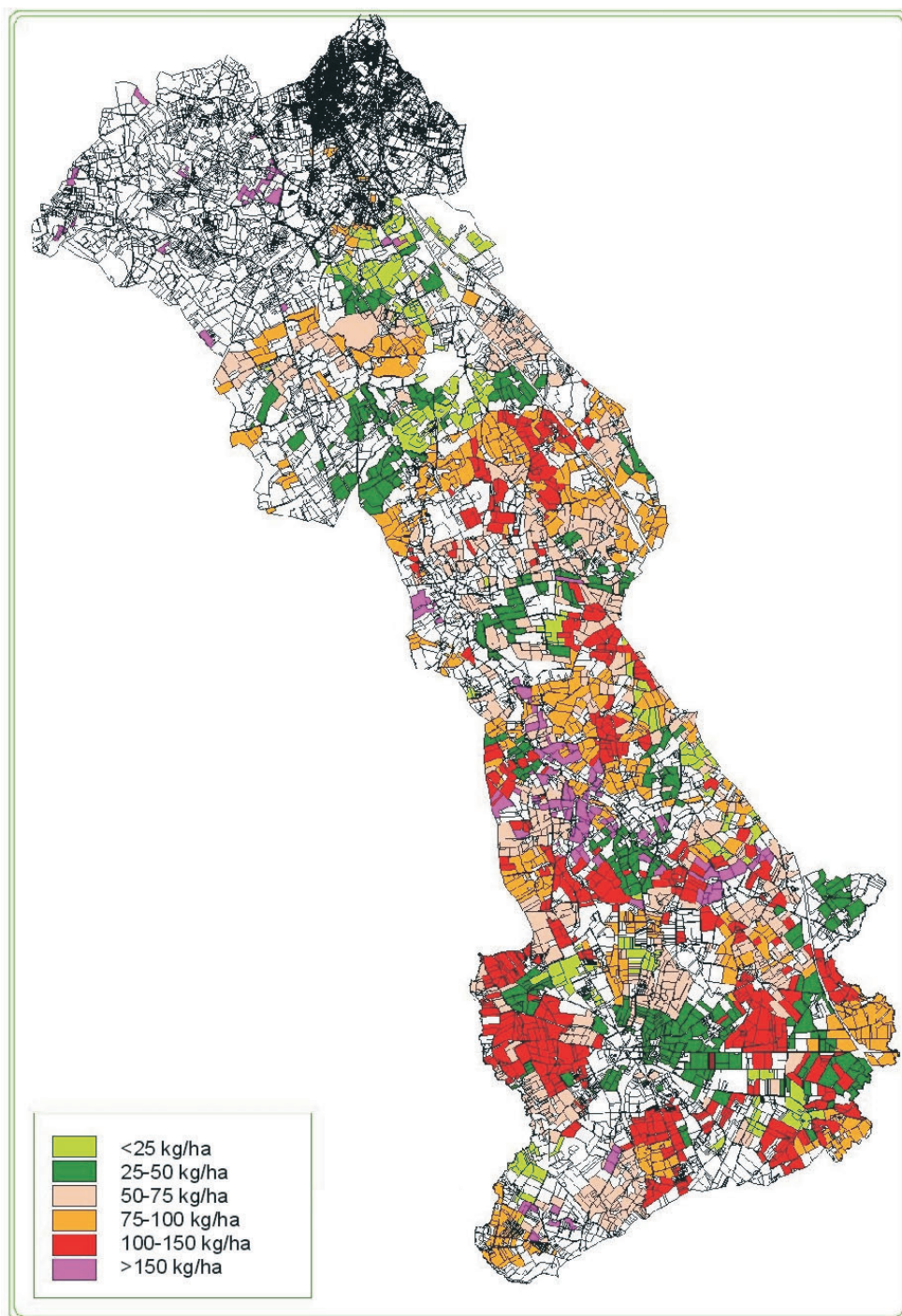


Figure 3a. Excess nitrogen in the fields of the Ognon watershed in 1995 (a).

4.2. Environmental indicators

The major difficulty in evaluating the environmental impact of practices is that it generally cannot be directly perceived at the level of the field. This makes it difficult to make the farmer aware of his contribution to environmental nuisances. For example, the eutrophication of surface wa-

ters, air pollution with greenhouse gases or the pollution of ground water with nitrate are observed far from the farms responsible. Thus, to evaluate the environmental impact of practices at the field or farm levels, environmental indicators correlated to the contribution of the field or the farm to the global nuisance have been developed (for example, [6, 26]).

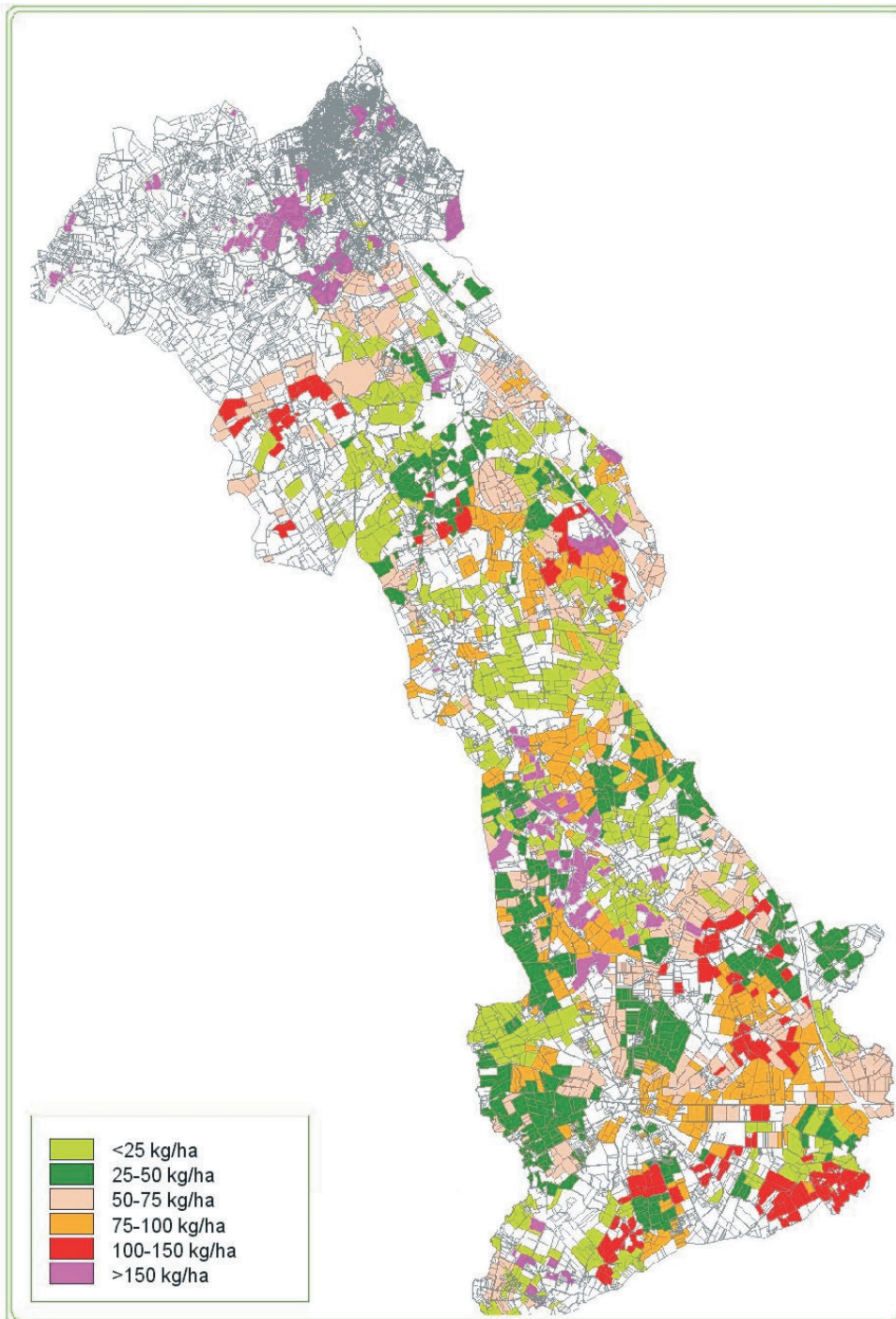


Figure 3b. Excess nitrogen in the fields of the Ognon watershed in 2000 (b).

Undoubtedly, it is for estimating the risk of nitrate leaching that most indicators are available, for use on the field, farm or catchment scales [16, 60, 62, 64]. They are currently used by agricultural advisors in collective nitrogen management operations. The following example [42] illustrates the use of a very simple indicator to estimate the potential nitrogen excess: the N budget of the whole farm (imports minus

exports of the farm, where imports correspond to the N present in fertilisers, industrial or urban effluents and animal feed bought, and exports correspond to the N content of farm products sold). This indicator was calculated for all the 150 farms of a catchment area in western France (13000 ha) in 1995 (Fig. 3a) and in 2000 (Fig. 3b). In 1995, it was found that this zone generated a potential excess of 568 Mg of nitrogen, with

55% of the farms responsible for 80% of this excess. The southern part of the area, a zone of intensive dairy farming, was the principal cause of the problem. This finding was used to design an action plan aimed at the farms with the largest nitrogen excesses (advice about the valorisation of animal effluents by using them as fertiliser for both arable and grazing land, and reduction of additional mineral fertiliser use). The indicator was recalculated in 2000, after changes in the management of farmyard and liquid manures. The potential excess in this area was found to have decreased by 23%, having fallen to 437 Mg in 2000.

As shown by this example, such indicators aim primarily at grading situations, which is very useful (i) to identify the situations in which improvements must be a matter of priority, and (ii) to monitor the efficacy of changes [6]. In recent years, the number of indicators of nitrogen pollution has grown as a consequence of the increasing demands for tools for assessing cropping systems. Most, like the example indicator described above, were designed so as to be straightforward to calculate, with data easily available to the farmer or in agricultural statistics. This constraint imposes simplifications on the inclusion of nitrogen cycle processes, and the consequences of such simplification are not always clearly appreciated by users. A comparative analysis and a validation of the various indicators available is required, but would not be straightforward because the impacts that they are intended to reveal are detected and measurable on different scales [7]. Nitrogen cycle process specialists should be more involved than has been the case in the research aimed at designing and evaluating such indicators. This would favour mechanistic models being better valorised, and promote the possibility of performing and using simple field measurements [16].

5. ACT: THE SET OF THE PRIORITIES FOR THE NEXT LOOP

In the last step of the quality spiral (ACT), stakeholders analyse the results of their environmental management and set priorities for the next loop. This involves determining which aspect of the plan or its implementation should be reconsidered so as to resolve the problems identified during the CHECK step. However, the information provided by the indicators is often insufficient to identify improvements in practices that could resolve the environmental problem detected. Indeed, technical actions often interact and it is rare that an environmental problem results from a single action. For example, let us assume that an indicator of a high risk of pesticide pollution shows that a farmer uses too much pesticide, or that he uses active ingredients that are too aggressive for the environment. In some cases, this may be due to proven overconsumption with respect to pest problems and the solution is the rationalisation of pesticide application. However, in many cases, the use of large amounts of pesticides is justified by the risk to plant health, and the most successful action would be to reduce this risk. The solution may thus be, according to the situation, to cultivate pest-resistant varieties,

modify the crop rotation, change the choice of the nitrate catch crop or fertilisation methods, or more than one of these.

Few diagnosis tools are available for tracing back the causes of environmental problems in a systemic manner, at the level of the whole cropping system. The aim of such tools would be to identify categories of situations in which the priorities for action differ. There is an urgent need to conduct research specifically targeted at developing such tools, which are essential for completing the loop and thereby allowing progress.

Table III shows an example of such categorisation of agricultural situations for arable crops [61], proposed as a means of diagnosing risks of nitrate pollution and directing the choice of solutions, and which is used in France in local development operations ("Ferti-Mieux" operations [37]). The fields are classified according to two criteria: one assessing the probability that the nitrate present in the first few centimetres of soil at the end of the autumn will be leached during the winter beyond the zone accessible to the roots of the crops grown in the rotation, and the second assessing the probability of a low N recovery, linked, for example, to the intensity of water stress.

- Situation F corresponds to shallow soils (rendzinas, for example) in climates with a significant summer drought. The adjustment of nitrogen fertilisation is difficult because crop yields vary considerably from one year to the next and crop nitrogen requirement is hard to predict. The nitrogen present in the soil in autumn due to excessive fertilisation and mineralisation during autumn, is leached during winter and, in general, cannot be captured by the roots after the winter period. The sowing, every autumn, of a nitrate-trapping crop is essential to limit nitrate leaching.
- The use of irrigation makes it possible to move on to situation C and to reduce environmental risks, provided that the water supply is well controlled.
- Situation A corresponds, for example, to deep loamy soils. The adjustment of N fertilisation is easier: the nitrate level in the soil in autumn is less variable and, after winter leaching, the nitrate present may be recuperated by the subsequent crop; a nitrate catch crop is generally not necessary during winter, but the measurement of mineral nitrogen in the soil at the end of winter is of prime importance to facilitate the adaptation of fertilisation.

Table III. Categorisation of agricultural situations, proposed as a means of diagnosing risks of nitrate leaching for arable cropping systems (after Sebillotte and Meynard [61]).

		Risks of nitrate leaching during one winter beyond the reach of the deepest roots of the crops grown in the rotation		
		Nil to low	Intermediate	High to certain
Variability between years in nitrogen recovery	Low	A	B	C
	High	D	E	F

- Situation D corresponds to deep, hydromorphic soils. The crop nitrogen requirements on such soils are irregular, but any excess fertiliser applied can be recuperated by the following crop. The use of a nitrate-trapping crop is, however, justified if excess fertilisation occurs for several consecutive years.

Such an environmental diagnosis combines indicators for the identification and grading of problems with tools for the categorisation of situations, making it possible to identify solutions to reduce environmental problems. If the results of the environmental diagnosis are not satisfactory, the farmer should change his cropping systems or adopt new decision support tools, the advisor should modify the construction of his advice and the authorities should modify their regulations or initiate actions to promote environment-friendly practices. The improvements in cropping systems finally enacted are generated by a combination of environmental diagnosis and analogue diagnosis focusing on production (yield and quality). Indeed, the modification of cropping systems to render them more environment-friendly must be compatible with the economic objectives of farming. The input data for categorisation tools, as for environmental indicators, should be easy to obtain, given that they are to be used on farms. One of the major issues in precision agriculture will be the collective capacity to make use of the considerable mass of spatial data concerning yield, canopy reflectance and soil quality, for agronomic and environmental diagnosis.

6. CONCLUSION

In this article we have used the hypothesis that it is possible to assess the needs for research into decision support tools for nitrogen management by organising analysis around the four steps of the quality spiral of environmental management. Faced with a very uncertain economic context, this approach makes it possible to reconcile the flexibility and sustainability of agricultural systems. This could, in the future, become a basis for environmental certification for the growing number of farms associated with agriculture, and even farms themselves, in addition to being a means of structuring agronomic reasoning for farmers and their partners (including advisors, suppliers and authorities). Because of the multiplicity of the stakeholders whose decisions affect agricultural practice, it is important that decision support tools not be aimed solely at farmers, and consider other scales of action than, as is classic, the field: the farm, the watershed, the supply basin for an agrofood business, and the administrative region, for instance. Our examples do not cover all these scales, in particular because there is a lack of many of the tools needed to make this approach feasible on all scales of decision-making or negotiation.

One of the main merits of this structuring of reasoning is that it reveals the substantial inequalities between work related to different steps of the approach: there has been substantial effort aimed at designing tools to control the nitrogen leakage to the environment (PLAN), but little consideration

during the design of these tools of the way in which they are used in practice (DO). There has been recent progress in the development of environmental indicators, but this has not as yet supplied genuinely validated tools (CHECK), and there is a severe lack of tools for linking evaluation based on the indicators to the definition of priorities for improvement (ACT). The progress spiral approach, which may appear natural to a decision-maker, is clearly not completely integrated into the definition of priorities for research programmes!

Entering into the progress spiral highlights, in particular, the prime importance of pursuing research on environmental diagnosis. It is still very difficult for a farmer or an advisor to evaluate cropping systems on the basis of criteria other than those linked to production and economic margins. Agriculture lacks validated tools and methods for environmental diagnosis. As a result, environmental criteria still have very little influence on the development of cropping systems. Agriculture will become truly sustainable only when all its stakeholders have the will and the means to evaluate regularly the environmental consequences of their actions.

The development of decision support tools has been frequently hampered by the availability of knowledge about the nitrogen cycle and its interactions with other components of the agrosystem. As it is already possible in many countries to use models and nutrition indices to determine fertiliser rates and dates, progress in the modelling of mid- and long-term changes in the carbon and nitrogen content of the soil will provide, in the near future, new tools for the management of nitrogen and organic matter at the level of the rotation [25, 56]. However, much less attention is paid to the understanding of the interaction between nitrogen management and integrated weed and pest management. This is particularly true as concerns the effect of nitrogen on competition between crops and weeds and on the development and detrimental effects of parasites, and the relationships between the decomposition of crop residues, changes in parasite inoculum levels, and the production of allelopathic and biofumigant compounds. These shortcomings in knowledge reduce both the predictive value of models used for technical considerations and also the quality of environmental diagnostic tools.

Finally, detailing the DO step illustrates the constraints affecting the implementation of tools and the diversity of their uses, aspects ignored by many biologists and agronomists. We need to integrate into the design of decision support tools more information about the way in which farmers and their advisors use these tools. To do this, the potential users should be involved in the design of these tools. One priority is the development of multidisciplinary research, making it possible to connect agronomic approaches involving indicators and models with social science approaches involving the use of cognitive tools, distributive decision support systems and the development of skills.

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