Design, assessment and improvement of crop management systems in sunflower

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Abstract

- This paper reviews different methods used to design, assess and improve crop management systems (CMS) in sunflower. The strengths and weaknesses of each method are shortly described and a general framework is suggested to combine them in a logical framework.
- Methods for designing and evaluating CMS have been developed for main grain crops combining participatory workshops, field test in experimental stations and pilot farms, evaluation using multi-attribute models and crop simulation. Some of these methods have been applied to sunflower.
- Sunflower crop models should integrate more biotic factors to predict actual yield and simulate the interactions between genotype, physical environment, management and the incidence and damage caused by pests, weeds and diseases. Decision-support models based on dynamic crop models should be developed and disseminated to make easier the use of models by extension services. Including virtual experiments in the dialogue between technical institutes, cooperatives, plant breeders and farmers will challenge the existing relations between the actors of innovation.

Keywords : factorial trials, system experiment, crop simulation, design methods, innovation

Introduction

In its main regions of production worldwide, sunflower crop is exposed alternatively to biotic (e.g fungal diseases, insects, birds…) and abiotic constraints (mainly drought…) (Schneiter, 1997). Therefore strategic and tactical crop management has to be optimized to cope with these multiple and often unpredictable stresses.

In France, the slow yield progress in commercial farms has been related to rainfed cultivation in shallow soils and southern regions, with poor technical and financial investment in crop management and no clear consideration of genotype (G) by environment (E) interactions (Jouffret et al., 2011). Consequently, the yield gap with genetic progress increased during the two last decades (Salvi and Pouzet, 2010). Similarly, in Argentina, a gap of at least 2 t.ha^{-1} was observed between actual and potential yield estimated in experimental plots (Lopez Pereira et al., 1999). Therefore opportunities exist to lift actual yield, provided the main restrictions to crop growth and yield are identified.

New outlets (specific oil quality, by-products…), new cropping opportunities (double cropping, organic farming, minimum tillage systems,…), recent technological (herbicide-tolerant cultivars..) and agronomical innovations (e.g. early sowing, very early cultivars, intercropping with legumes…) should require the re-design of current crop management systems (Jouffret et al., 2011). Conventional ones should be adapted as well to be more resource-efficient and optimize the G by E interactions. At the same time, new yield reduction factors are emerging in those regions where sunflower is frequently grown (e.g orobanche, verticillium wilt, premature ripening …) and adapted solutions should be found combining crop management and plant breeding.

Today, sunflower is already grown to fulfil multiple goals, but in a context where its competitiveness is often lower than cereals and oilseed rape, its importance is marginal for most of the farmers in France. Crop management should then be converted from a simple "sow then harvest" practice to a relevant set of decisions based on observations and robust rules. In addition, to be included more frequently in the cropping systems, the inter-annual fluctuations in yield should be controlled and the oil concentration payment should be more attractive for the farmers.

Fortunately, sunflower crop has proved real environmental advantages (low irrigation and N fertilization needs, low pesticides, good energy balance…) and opportunities may arise from these features in a general context of input reduction (Pilorgé, 2010). Sunflower is well adapted to organic farming and to drought-prone environments. It represents a substitute to maize in those regions where bans on irrigation are frequent. Whatever the scenario of climate change, sunflower as a C3 drought-tolerant crop should respond positively in the regions where water stress is moderate and it should spread towards colder regions with global warming (Tuck et al., 2006).

However, to benefit from these opportunities and reduce the yield gap with attainable yield, a framework should be proposed to organize the design, assessment, and improvement of sunflower crop management systems (CMS) and its insertion in crop rotations. Designing innovative CMS to fulfil economic, environmental and social requirements should be a routine process for agronomists.

In this paper, based mostly on French case studies, we will illustrate how different methods – often developed on other grain crops - could be combined for that objective in sunflower.

On-farm diagnosis of the yield-limiting factors

A first step involves describing and understanding the relationship between crop performances and farmers' practices (Byerlee et al., 1991). This diagnosis of agronomic problems has often been limited to surveys among farmers, in which they are asked about the problems they encounter.

A method called regional agronomic diagnosis was developed (Doré et al., 1997; Doré et al., 2008) in order to understand the variations in crop yield and quality and to assess the environmental impact on a regional scale. On a network of fields in a small region, during 2-3 years, the main limiting factors and their relative contribution are determined by collecting different environmental and plant data according to a yield build-up framework. From simple water and nitrogen budget models, a diagnosis on water and N plant nutrition is provided. These data are confronted to references under potential conditions (boundary lines, response curves) and the gap with actual data is calculated and interpreted according to detected yield limiting factors. Pairs of plots differing only by one significant factor can be sampled to limit the occurrence of confusing effects (Ribeyre et al., 1980).

Using this on-farm approach, Mercau et al. (2001) investigated constraints to actual yield of sunflower in 6 agroecological zones within the Argentine Pampas during 3 growing seasons on 250 large, grower-managed paddocks. Variation in yield among zones and seasons was analysed on the basis of biologically-founded assumptions. Low yield was associated with deficient ground cover in 25% of the crops ; part of the remaining variation in yield was accounted for by sets of measured variables particular

to each zone, including soil shallowness, low available P, low initial water content, weeds and diseases (verticillium, sclerotinia). The authors highlighted the positive role of rainfall favouring canopy expansion, resource capture, growth and yield, and its negative influence in the development of fungal diseases.

The variability of yield and oil content was surveyed during 3 years in two production basins of southwestern France (Champolivier et al., 2011; 2012). From this study (> 300 fields), it was concluded that farmers over-fertilized sunflower and that plant density was obviously too low for maximizing yield and oil concentration. The contributions of crop management and genotype in the variability of oil concentration were clearly separated. A crop model was used to help in the detection of crop water stress and to simulate attainable yield and oil production at field level (Casadebaig et al., 2011).

Such agronomic surveys (combining field observations and information on the practices) can be used to detect the most limiting and reducing factors and the technical weaknesses of current crop management. From this diagnostic, the extension services can revise their technical recommendations and ways of dissemination and better orientate the production of new references and decision rules.

Other types of surveys have been attempted to quantify crop practices (e.g postal enquiries). From this information, at national or regional levels, the discrepancy between actual practices and recommendations can be effectively quantified. More than 1000 volunteer farmers, probably the most concerned by technical improvement, generally answer to the CETIOM (the French technical institute for oilseed crops) national survey every two year (Lecomte and Nolot, 2011). Thanks to the size of the sample, unexpected facts become more visible. For instance, it appeared that boron was not applied where it was strictly necessary, i.e on shallow soils. Indeed, the priority is to spray where the risk of Phomopsis is high, mainly in deep soils. As the farmers are used to mix solute boron and fungicide in the same application (as recommended), boron is often applied in fields where it is not absolutely necessary.

In addition, from these surveys describing one representative field, typologies of CMS have been attempted using multivariate data analysis and classification methods in order to identify targets for advices (Salvi et al., 2012).

Factorial experiments to test the response of a limited number of agronomic factors

Mercau et al. (2001) emphasised the value of combining on-farm research that realistically quantifies yield response to key factors to experimental studies which provide biological background in the form of working hypotheses. Traditionally, factorial experiments are carried out to test the effect of one or several factors in combination on yield or grain quality. A huge number of response curves studies are found in the literature. The main factors which are compared on single experiments or multi-environment trials are: cultivars, N rate, irrigation amount, plant density, row width, levels of plant protection… The objective of these trials is to determine the best input rate to apply in average to the crop in a given production situation. In some trials, the factor levels (input amounts) are replaced by the difference to optimal rate (e.g. for nitrogen) or by indicators of satisfaction (Nitrogen Nutrition Index for N fertilization, ETa/ETo for irrigation practices). In some situations, up to 3 factors can be combined in split-plot designs to select the best combination of management practices in a given soil-weather condition.

However, building complete CMS through the compilation of these trials is an impossible challenge because of the multiple interactions between factors.

Testing crop management systems to reach objectives while satisfying constraints

Usually multi-factorial experiments compare the performances of crop management options defined by current standards (e.g. conventional, integrated or organic) without any clear reference to the design process. Debaeke et al. (2009) proposed a prototyping approach to design and evaluate CMS as relevant combinations of techniques. This loop approach is composed of 5 steps and the final output is transfer :

1)   definition of goals and constraints for each CMS ; constraints may result from soil and climate but also from environmental or economic concerns
2)   proposal of suitable agronomic strategies (such as escape, avoidance, tolerance or correction of limiting factors) to trigger at crop level
3)   formulation of relevant sets of technical rules, to put the strategies in action
4)   implementation of the action rules in large field experiments or pilot farms
5)   evaluation, refinement and eventually re-design of the CMSs if not valuable
6)   test and transfer the most innovative ones to practitioners

The design process (building cropping systems compatible with the set of constraints) is initialized with existing knowledge and the skill of experts during participatory workshops (Lançon et al, 2007). The

experimental design is composed of a limited number of relevant combinations of techniques, built to fulfil the farmer's objectives (e.g. maximizing gross margin, reducing labour time) while complying with the environmental regulations (e.g. maximal amount of water or nitrogen), or to cope with more demanding environmental aims (e.g. reducing dramatically greenhouse gases emissions, reducing the reliance on pesticides). To reduce the number of systems to test, expert knowledge or models are used to design and select *ex ante* the most promising CMS candidate(s) before a complete field experiment process (Sadok et al., 2009).

A main feature of this method is to put the systems in action by means of action rules as: "if [indicator] then [action 1], else [action 2]". As a consequence, the techniques are not fixed but result conditionally from weather conditions, crop and pest development or soil status. To trigger most rules in practice, indicators of soil/plant/pest status are observed or simulated and then compared to a reference or a threshold value. The rules cover all the decisions of a CMS including the cultivar choice. Consequently, the details of the crop/pest management techniques may change with locations and seasons while the agronomic strategy remains unchanged.

The evaluation process includes three levels : (1) global, multi-criteria and comprehensive, to test if the CMS globally fits with the assigned objectives, using data collected at harvest or agri-environmental indicators; (2) agronomic, based on dynamic simulation or field measurements, to test the validity of the assumptions underlying the CMS design; (3) analytical, to thoroughly evaluate some elementary decision rules. An important feature however is that data collected for the CMS evaluation should be clearly separated from data used for rule triggering.

Several studies have been conducted on wheat CMS (e.g. Loyce et al., 2008). Comparisons of CMS were operated by CETIOM in the 90s in response to major changes in the Common Agricultural Policy: 3 systems were designed as 'insurance : maximum yield whatever the costs ', 'technical : no systematic applications', and 'economy : low costs' (Leterme and Wagner, 1993). In Toulouse, different programs were based on the design and evaluation of sunflower CMS to face irrigation availability. Plant density, variety choice, N fertilization, and fungicide protection were adjusted to expected yield and drought risk (Debaeke et al., 1998 ; 2003).

Crop models may be used to simulate numerous management-environment combinations

Among the tools available for evaluating CMS or investigating alternatives, field-based approaches such as regional agronomic diagnosis and prototyping (e.g. Lançon et al., 2007) have been tested and used successfully on a range of grain crops. However, these approaches are too slow to provide timely responses to such rapid contextual changes and are unable to explore a large number of systems. *In silico* approaches, based on the study of a wider range of possible systems through modelling and simulation, offer the possibility of identifying more quickly new systems to tackle agronomical and environmental concerns (Bergez et al., 2010).

Crop simulation models have been developed as surrogates to multi-factorial and multi-environment trials by their ability to multiply the situations (soil, weather, management…) to be tested and by providing additional dynamic variables which cannot be monitored daily throughout the crop cycle (e.g. N and water in soil). Numerous crop models have been regularly developed since the 70s following the de Wit and Monteith principles. Villalobos (2000) at the 15th ISC (Toulouse) and Flénet et al. (2008) at the 17th ISC (Cordoba) reviewed the different sunflower models and their applications. More recently, De Carvalho Lopes et al. (2011) completed this review for models applicable to biodiesel production. Presently, some models are sunflower-specific, and a few others are generic with a specific parameterization for sunflower. Todorovic et al. (2009) compared the performance of 3 generic models: AquaCrop, CropSyst and WOFOST. A new model (SUNFLO) was developed by Casadebaig et al (2011) to represent more explicitly the cultivar performances and the G by E interactions.

Since the pioneer study of Sadras and Hall (1989), these models have been extensively used to compare the effects of various management strategies (Flénet et al., 2008): sowing date, irrigation, N management, planting density, maturity group or cultivar. Multi-simulations are used to optimize crop management, by considering crop response (yield) to long-term historical weather records. Cumulative probability curves are then figured with the simulation results to facilitate the comparisons.

For instance, the interest of early sowing was generalized by simulating rainfed sunflower yields, under early January and mid-March plantings, for a 25-year period with the aid of OILCROP-SUN model which has been validated in southern Spain (Soriano et al., 2004). From the model, the authors concluded that early plantings of sunflower increase rainfed yields ($Y = T \times TE \times HI$) by increasing both Transpiration (T) and Transpiration Efficiency (TE), while the impact of planting date on HI very much depends on the crop water stress pattern, which is quite variable from year to year.

Similarly, Rinaldi (2001) used the EPIC model to optimize irrigation scheduling in southern Italy. The model, calibrated and validated in previous studies, was run for a 45-year simulation with daily climatic data, using 66 scenarios involving a combination of irrigation times (at 5 fixed data), seasonal irrigation amounts (from 0 to 200 mm) and irrigation frequency. The results indicated the superiority of single or double irrigation in the central phase (bud flower opening, flowering), the optimal value of seasonal irrigation water to be about 250-300 mm for the highest WUE value and the highest profitability for the farmer achieved with a single irrigation of 200 mm at bud flower phase and a reduction of net income with irrigation at sowing or at seed ripening phases.

However, the sunflower models did not simulate until now the yield reducing effects of fungal diseases, insects or weeds. That is why the models were generally optimistic and favoured high input management considering *de facto* a full control of pest, weeds and diseases. An attempt was published by Debaeke and Estragnat (2003) to relate CMS, leaf area index and Phomopsis stem canker incidence and damage but without detailing the underlying biophysical processes. The WHEATPEST model (Willocquet et al., 2008) where the damage profile of the wheat bio-agressors is simulated for different production situations could be an example to follow on sunflower crop.

We feel that the simulations outputs could assist farmers in making strategic management decisions by providing information on the effect of one or several cultural operations, in each specific soil x climate situation, accounting for the variability between years. However, the users of crop models should be aware of the accuracy, robustness, and relevance of the models they are using (Flénet et al., 2008).

Designing crop management systems from simulation process

Designing CMS with simulations can follow a four-step iterative process described by Bergez et al (2010) as the GESC loop :

G: Generation of a set of candidate crop management plans either randomly created or provided by the user.

S: Simulation of the management plans in soil/weather/constraints contexts.

E: Evaluation of the simulated management plans

C: Comparison and choice of the most satisfying crop management options and/or improvement through a new generation process that loops to step 1.

Accordingly, different methodologies are used to carry out the GSEC loop. A first approach is to create a large set of strategies, either based on date and quantity parameters or on decision-rule parameters. Each strategy is simulated and evaluated, and then a selection method is applied to the large set of results, ranging from blind generation up to complex algorithms. A second approach consists of generating new strategies from the initial population during the simulation process by an evolutionary process concentrating on the most promising population within the decision space. Some systems may lead to good results for some indicators and less satisfactory results for others. This decision-making problem can be handled by multi-criteria decision aid (MCDA) algorithms.

Conclusions

The proposal of innovative CMS in sunflower should emerge from the different ways shortly described in this paper. First of all, field and farm surveys at local scale, completed by national and regional statistics, are the most efficient methods for quantifying the reality of crop practices and performances. Yield gaps and the relations between performances (seed yield, oil…) and practices could be analysed with agronomic diagnosis and simulation models. The definition and ordering of objectives and constraints of crop production, which constitute the first step of CMS improvement, must result from interviews with farmers and other actors of oil supply chain. Quantitative and qualitative models may help in the *ex ante* evaluation of CMS (from 'promising' to 'candidate' CMS) (Sadok et al., 2009). Innovative systems can be imported directly from the farm and scientifically evaluated by research. Candidate CMS should be evaluated on experimental stations or pilot farms using agricultural machinery and realistic plot size. Both indicators and measurements should be used to evaluate the CMS according to the objectives and constraints. Multi-criteria methods would be then necessary to aggregate the different components of sustainability. This chain of design and evaluation is a problem-solving process which has been described in industry as the continuous improvement loop (Plan-Do-Check-Act).

Because of their central role in CMS improvement, sunflower models should be improved as well to account for more biotic reducing factors. Decision-support systems should be developed to better use the underlying crop models and facilitate their transfer to advisers (Champolivier et al., 2012). Routine experiments (mono-factorial) probably could be replaced more and more by *in silico* evaluation using

robust crop models. Undoubtedly, this will change the relations between technical institutes, farmers, cooperatives and breeders who are all concerned by advices.

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