Yield gap assessment and diagnosis in Brazil using a crop model

Fran?ois Affholder[1], Jose Madeira Netto[2] and Eric Scopel[3]

[1] CIRAD www.cirad.fr / IRRI www.irri.org Email affholder@cirad.fr
[2] EMBRAPA / ENSAM www.embrapa.br Email mailto:madeira@ensam.inra.fr
[3] CIRAD/EMBRAPA www.cirad.fr Email eric@cpac.embrapa.br

Abstract

In order to reduce locally the gap between potential and real yields, its causes must be diagnosed. Through a case study on maize in small-scale farms of central Brazil, this poster presents an approach for this purpose, taking advantage of the advances in crop modelling. Based on an on-farm survey and on the building and use of an *ad hoc* crop model, this method facilitates the detection of constraints and the assessment of their impact on local yields, although it does not suppress all subjectivity in the diagnosis. STICS, an existing crop model, had to be improved for the specific purpose of the study, in order to take into account Aluminum toxicity, water excess and competition between crop and weeds for light, water and nitrogen. The local diagnosis showed that most of the yield gap was due to inappropriate crop establishment, itself resulting from shortcomings of associations of farmers in managing the collective farm machinery.

Media summary

Crop models have become powerful tools for diagnosing the causes of yield losses, a pre-requisite for improving the performances of cropping systems in developing countries.

Key Words

Cropping systems, yield variability, field survey.

Introduction

Although improving crop yields may not be a priority for many developed countries, it remains an important goal for small-scale farms of the developing world. This requires that the causes of the gap between potential and real yields are identified. On one hand, many interacting variables are theoretically involved in yield variability in natural environment, so that building a standard statistical design aiming at assessing the specific role of each variable in yield gap would be impracticable. As a result, subjectivity is probably not fully avoidable in gap analysis studies. On the other hand, interviews of farmers are certainly too speculative. They are known to frequently mistake symptoms of yield and growth reductions for their causes (Dor? *et al*., 1997). This paper presents the broad outline of a case study in which crop modeling was used in an attempt to introduce more objectivity in this difficult task.

Study context

The methodology was applied to a 2500 km^2 region of central Brazil, the Silv?nia *municipio*, where the family-farm system underwent an agrarian revolution during the last decade, and where a joint EMBRAPA/ CIRAD research and development project took place to study and facilitate the development process. When they gained access to credit and market (thanks to collective action of farmers and to a favorable state policy) many of the subsistence farms of this region turned into intensive dairy farms, providing decent income to the farmers. Of course the dramatic changes in farming systems implied changes of similar extent in cropping systems. Maize, used for feeding livestock, became the key crop of these farms, and cropping systems based on manual and animal-drawn tillage with no or very few inputs were replaced by intensive systems that included the use of fertilizers, improved cultivars, and tillage machinery (Bainville, 2000). However at the early stages of these technical changes, a rapid appraisal showed that yields were still very low compared to what was *a priori* expected from the techniques used and the local environment, and also that these yields were highly varying across fields. This led us to perform a yield gap analysis for maize. The paper reports on this specific task of the R&D project. A sample of 50, 25 m2 plots was set in farmers' fields selected to cover the local diversity of management and environment. These plots were monitored over three years. Data were collected on technical management, main physical and chemical characteristics of the soil, weed infestation and damages due to pests and diseases, and crop growth and development.

A crop model as a tool for identifying constraints

Instead of studying the yield gap between actual yields and a "potential" resulting solely from variations in solar radiation, temperature, and cultivars' characteristics, a "reduced gap" was considered (Fig. 1), between actual yields and the yield simulated with Stics, a crop model simulating the potential yield and the yield reduced, through the use of stress functions, by water and nitrogen stresses.

Stics simulates at a daily time step leaf area index, above ground biomass, grain yield, root distribution in soil profile, water and nitrogen content in a soil assumed to be a stack of 1cm thick soil layers. Stics also accounts for yield reductions when stand, below a threshold characteristic of the cultivar used, limits radiation intercepted by leaves (Brisson *et al*., 2003). Stics had been successfully calibrated and validated for the local conditions prior to the study (Affholder *et al*., 2003).

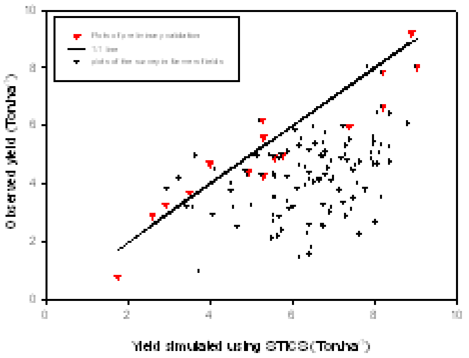

Figure 1. Relation between observed yields and STICS-simulated yields resulting from the effects of plant density, water and nitrogen constraints on yield permitted by solar radiation, temperature, and cultivar's characteristics.

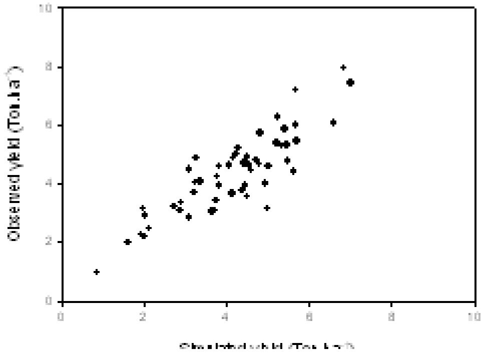

Figure 2. Partial validation of Stics as modified in order to account for the constraints Weeds, Aluminum toxicity, and Water excess.

Although still high on average and highly variable across situations, the "reduced" gap was found easier to address than the "overall" gap relative to potential yield, because of a lower number of interacting factors possibly involved in the former than in the latter. Correlations were sought between the "reduced gap" and those of the variables monitored in the plots that were not used as input parameter in the simulations. This allowed us to determine (data not shown) that the constraints responsible for yield reductions, additionally to those accounted for by Stics, were mostly: weeds, aluminum toxicity in soils, and water excess possibly provoking anoxia. At this stage of the analysis, it was not possible to assess the extent to which each of these constraints was limiting yields, as they were in most cases simultaneously present in the fields.

Ad hoc modeling

Stics was improved so as to enable simulation of the effects on yield of the constraints identified at the previous step of the analysis. This was done without attempting to maintain the generic feature or the wide validity domain of the genuine STICS, but rather aiming at an *ad hoc* model, according to Sinclair and Seligman (1996), i.e. a model specifically designed for the purpose and context of our study. In accordance with experimental work conducted by EMBRAPA in acid soils of central Brazil (Silva and Ritchey, 1982), Al toxicity was taken into account by setting a 45% threshold of saturation of CEC by Al, below which roots were assumed to grow normally, and over which root growth was assumed to be zero. On days when soil moisture was simulated as over field capacity at the depth of the rooting front, the simulated descent of rooting front was also stopped. The introduction of weed competition with crop required a greater modeling effort. It appeared necessary to take into account dynamically the competition for light, water and nitrogen, unless no satisfactory calibration was obtained. This was done by considering theoretical mechanisms described in literature and available process-oriented models (Kiniry *et al*., 1992), but introducing simplifying assumptions permitted by the restricted scope of the model to be built. Those were mainly that the botanical composition of the weed community and the seed bank in soil were assumed to be constant across fields of the region. Also, a single root system was considered for both maize and weeds. The resulting model was calibrated using a subsample of the plot sample and partially validated using the whole plot sample (Fig. 2). The overall good agreement between simulated and observed yields indicated that most of the causes of yield variability in the region under study were adequately accounted for by the modified model.

Experimenting with the model

As a third step of the analysis, the model was used to estimate the impact on yield of each specific constraint, plant density, water and nitrogen stresses, aluminum toxicity, weeds and water excess. First, the main effect of each constraint was evaluated. This was performed by building a "virtual experiment" in which, to each actual plot of the sample, corresponds a set of simulated plots differing one from another by the values chosen for input parameters of the simulations. These parameters were given two levels: the level measured in the plot, and a reference level, defined so that when all parameters at are reference levels the simulated yield is equal to the potential yield. For each plot in the sample, a trait "water constraint alone" was defined by setting simultaneously at their measured values all the input parameters involved in the calculation of the water stress, whereas all the other input parameters were set at their reference value. Similarly traits "Nitrogen constraint alone", "stand constraint alone" and "weeds constraint alone" were defined. Thus, estimates of the main effects of water, nitrogen, stand and weed constraints were obtained for each actual plot by comparing the simulated yields of these virtual traits to the simulated potential yield. The difference between potential yield and the yield of each one of the virtual traits, averaged for the whole plot sample, was assumed to measure the weight of the main effect of the corresponding constraint in yield reductions at regional level (fig 3).

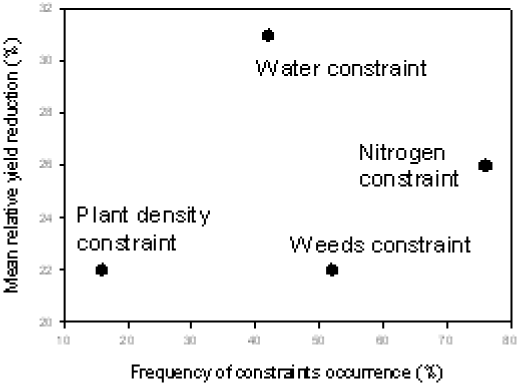

Figure 3. Main effect of constraints, as

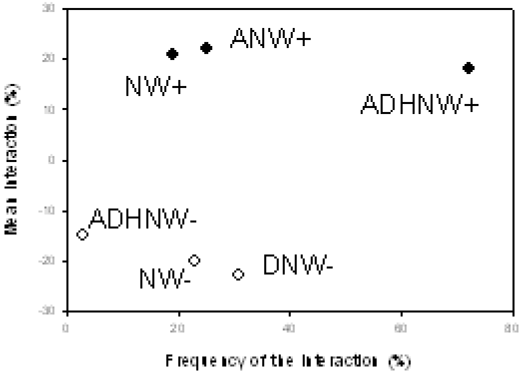

Figure 4. Simulated interactions between the

simulated using Stics-modified. Frequency of occurrence: proportion of plots in which simulated yield reduction in relation to simulated yield potential (relative yield reduction) was over 10%, taking into account the observed level for the considered constraint and unlimiting levels for the other constraints. Relative yield reduction was averaged over the plot sample, discarding plots with yield reduction below 10%.

modeled constraints using Stics-modified. Interaction is the difference between the overall effect of a set of constraints (represented by the block letters, see below) and the sum of the main effects of each constraint in the set. Interactions were averaged separately (see text) for negative (-) and positive cases (+). A: Al toxicity; D: plant density; H: weeds; N: nitrogen; W: water.

It must be noted that the main effects of Aluminum and water excess constraints were not assessed. Indeed, given the assumptions made in our modified version of Stics, reductions in root depth due to these constraints do not have any consequence on the simulated yield unless water or nitrogen are also limiting. The regional impact of Al toxicity and water excess constraints was thus assessed through the study of interactions between constraints. Similarly, virtual traits were defined by setting at observed values the input parameters related to a subset of constraints, while parameters related to the complementary subset were set at reference values. The subsets studied were covering all the possible combinations of the constraints taken into account by the model, in order to simulate all the possible interactions between constraints. The results were averaged across the whole plot sample, except that cases of negative interactions (i.e. cases where yield reductions due to interactions between constraints were lower than the sum of the main effects of the considered constraints) were averaged separately from the cases of positive interactions (yield gap aggravated by the interactions between constraints as compared to the sum of main effects on yield gap). The main results are shown in Fig.4, where yield reductions lower than 20% of potential yield are not displayed, the overall error of the model being close to 20%.

The study was finally refined by applying the same principles of experimenting with the model, in order to better understand the specific role of each of the parameters involved in the main constraints at play according to the preceding. This allowed us to determine (data not shown) that it was possible to reduce substantially the yield gap by improving the technical management at crop establishment. Particularly, the main weaknesses of the cropping systems were inappropriate sowing dates, N-fertilization, weeding sequences, as well as delays between tillage and sowing that were favouring weed growth. Most of these causes of yield losses were found to result from shortcomings (by associations of farmers) in managing the collective farm machinery. We believe that our study, by providing estimates of the consequences on yields of this inadequate management, played a key role in supporting the efforts of farmers for improving yields.

Discussion and conclusion

The use of a crop model first facilitated the detection of constraints involved in yield variations in a network of farmers' fields. Second, it allowed us to estimate the impact of these constraints. As there is no universal model capable of simulating growth and yield of any crop at any location, under any technical management, it is likely that at least some modeling work is unavoidable as an intermediary step between the detection of constraints and the assessment of their impact. Modeling is often seen as extremely time consuming and thus hardly compatible with R/D research in which scientists are expected to provide quick solutions to farmers' problems. However, with the development of modern modeling tools with data-base oriented management of input and output data, the scientist can concentrate on writing his model's equations rather than on programming access to data. These tools also facilitate greatly experimenting with the model, since the combinatory sets of parameters required for this purpose may be easily generated by today's databases softwares. We lacked space, in this poster paper, to present our work on the assessment of model errors and the way they may affect the conclusions of the study, and interested readers may refer to Affholder et al. (2003) for a more complete report. It should be underlined here, however, that a rigorous evaluation of errors associated to the estimates of the impacts of each constraint would require a standard statistical device allowing variance analysis. As a result, the use of expertise, which implies some subjectivity, probably remains unavoidable for a diagnosis where such a statistical device is impracticable. The use we made of a crop model should not be seen as an attempt to fully replace such a device, but rather as a powerful tool in assisting the expert in performing a diagnosis.

The key variable studied in this work was yield, and according to what seems to be a strong trend, yield may no longer be the key variable describing the performances of cropping systems. Indeed, it tends to be replaced by variables describing the quality of the production or the impact of the cropping systems on the environment. However, as far as these variables are the product of interactions between technical management, a crop and its environment, the approach used in the present study may apply to the general purpose, that may be called "regional analysis of cropping systems", i.e. assessing the performance of cropping systems across a region with heterogeneous environment and technical practices.

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