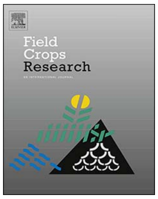
Field Crops Research 210 (2017) 114–128

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr



Ambitious environmental and economic goals for the future of agriculture are unequally achieved by innovative cropping systems

Caroline Colnenne-David[a,*], Gilles Grandeau[a], Marie-Hélène Jeuffroy[a], Thierry Dore[b]

[a] Inra, UMR 211 Agronomie, 78850 Thiverval-Grignon, France
[b] AgroParisTech, UMR 211 Agronomie, 78850 Thiverval-Grignon

ARTICLE INFO

Keywords:
Cropping system experiment
Field assessment
Greenhouse gas emissions
Pesticide
Energy

ABSTRACT

Agriculture has to face huge challenges in the decades ahead. Four innovative cropping systems were assessed in a “cropping system experiment” in the Ile-de-France region (France) from 2009 to 2014. Three were designed to meet ambitious goals: the total elimination of pesticides (No-Pest), reducing fossil energy consumption by 50% (L-EN), or decreasing greenhouse gas (GHG) emissions by 50% (L-GHG). They were also required to satisfy a wide range of environmental criteria and to maximize yields whilst respecting the major constraint on the system and the environmental targets set. A fourth system (PHEP), in which the environmental and yield targets were achieved with no major constraint, was also assessed. After completion of the first full crop sequence for these innovative systems, the results obtained indicated that it was possible to design and implement innovative systems achieving multiple goals. In our field trial conditions, the pesticide and energy constraints were almost satisfied, whereas the GHG target was missed by a considerable margin. All four innovative systems satisfied environmental criteria in terms of N management, pesticide use, energy consumption and crop diversity. However, herbicide treatment frequency index (TFIH) was higher than expected in the two systems with no-plow practices, L-EN and L-GHG. In the pesticide-free system, soil organic matter content was lower than expected, due to frequent plowing (every 2 years) and low residue levels as a result of the lower yields obtained. Yields were lower for the L-EN system than for the reference system, and yield was variable in the L-GHG system. These innovative systems had better environmental performances than the systems currently used in the Ile-de-France region, with no decrease in gross margins.

1. Introduction

New challenges are continually arising in agriculture, necessitating profound breakthrough innovations in agricultural practices. The most serious issues faced concern: (1) the loss of biodiversity in agroecosystems, (2) the need to reduce chemical inputs, which are known to be harmful to the environment and human health, and (3) the need to decrease the impact of agriculture on climate change, by decreasing greenhouse gas emissions and promoting carbon storage in the soil. Current arable cropping systems are of questionable sustainability, and alternative cropping systems must therefore be designed, to meet the goals of a more sustainable agriculture. Agronomists design and assess innovative cropping systems to tackle a wide range of issues (Doré et al., 2011; Blazy et al., 2009; Sadok et al., 2009). Moreover, given that global food security has become a primary concern (Charles et al., 2016), there is a need for innovative cropping systems that increase agricultural resource use efficiency (Foley et al., 2011).

New strategies for crop management and new cropping systems have been designed in recent years. Many have targeted a single principal goal, such as enhancing C sequestration through changes in crop management (*e.g.,* Freibauer et al., 2004; Dimassi et al., 2014), reducing pesticide use (Aubertot et al., 2005; Chikowo et al., 2009), decreasing energy consumption (Singh et al., 2008; Khakbazan et al., 2009), or improving the yield of a single crop (Tapia et al., 2014). However, some studies were “innovation-pushed”: the authors compared cropping systems on the basis of the combination of agricultural practices used (Kulak et al., 2013), rather than on the achievement of target performances with the most appropriate practices. For example, they compared organic and conventional systems (Panasiewiez et al., 2010; Nemecek et al., 2011a), or no-tillage and conventional tillage systems (Abdi et al., 2014; Dimassi et al., 2014), without providing any further information about the objectives to be reached. In most of these examples, only a few criteria were assessed in field trials: the distribution of phosphorus species in the soil profile (Abdi et al., 2014),

---

[*] Corresponding author.
E-mail addresses: caroline.colnenne-david@inra.fr (C. Colnenne-David), gilles.grandeau@inra.fr (G. Grandeau), marie-helene.jeuffroy@inra.fr (M.-H. Jeuffroy), thierry.dore@agroparistech.fr (T. Dore).

http://dx.doi.org/10.1016/j.fcr.2017.05.009
Received 21 September 2016; Received in revised form 10 May 2017; Accepted 12 May 2017

changes in soil structure and yield performances (Abdollahi et al., 2015), soil biological properties (Ingle et al., 2014), ecophysiological characteristics of spring barley and genotypes under various systems (Panasiewiez et al., 2010), and weed infestation under different long-term tillage systems (Chikowo et al., 2009). However, in some cases, multi-criteria analyses were performed, with various methodologies (Nemecek et al., 2011a, 2011b; Loyce et al., 2012; Kulak et al., 2013). These multi-criteria assessments made it possible to analyze combinations of agricultural practices with opposite impacts on specific criteria, and to consider trade-offs. For example, no-till systems decrease energy consumption, but increase herbicide use (Zentner et al., 2004).

To our knowledge, no study has yet both (i) designed *in silico* innovative and consistent cropping systems addressing a multiplicity of current issues, and (ii) assessed them in a cropping system experiment involving the analysis of multiple performances. We designed *in silico* innovative cropping systems addressing multiple issues of importance (Colnenne-David and Doré, 2015), and conducted system experiments to assess their ability to achieve several goals. Four innovative cropping systems targeting various environmental goals and yield objectives were designed by the prototyping method described by Vereijken (1997). Their performances were assessed *ex ante* with various tools and models: the Indigo® method (www7.inra.fr/indigo) for environmental performances, the Simeos® tool (using the AMG model, Andriulo et al., 1999) and the Roth C model for carbon sequestration, as in the study by Colnenne-David and Doré (2015). For each combination of objectives, the most promising candidate system was then implemented in a cropping system experiment.

We present here the field trial results for these four innovative cropping systems, for the first full crop sequence. We analyzed the performance of the cropping systems in several different ways: (1) we compared the innovative cropping systems implemented in the field trial with the prototypes (Colnenne-David and Doré, 2015); (2) we compared the three innovative systems designed to meet particular constraints with a constraint-free innovative system used as the reference system and (3) we compared the innovative systems and the current system in the Ile-de-France region, where the field trial took place.

2. Materials and methods

2.1. General description of the four innovative cropping systems

Four innovative cropping systems with quantified constraints, and environmental and yield targets were designed jointly with various stakeholders, including farmers, in 2008 (Table 1, Colnenne-David and Doré, 2015). The “productive with high environmental performance” (PHEP) system was designed to minimize environmental impact (decreasing nitrate and pesticide pollution, enhancing crop diversity or reducing fossil energy consumption relative to current cropping systems) and to reach the maximum possible yield given the environmental targets, as described by Colnenne-David and Doré (2015). This cropping system, which was designed without major environmental constraints, was used as the reference system for comparisons with the other systems. Each of the other three systems was designed to meet an additional environmental constraint, constituting a major breakthrough in terms of the objectives for current cropping systems: the elimination of pesticide use (No-Pest), reducing fossil energy consumption by 50% relative to the PHEP system (L-EN), or halving greenhouse gas emissions relative to the PHEP system (L-GHG). These cropping systems were also designed to minimize environmental impact whilst providing the maximum possible yield under the constraint imposed and respecting the environmental targets. During the design step, the constraints and targets were prioritized as follows: the environmental constraint had to be satisfied first, the set of other environmental targets then had to be attained, and, finally, yield had to be maximized. The systems retained for field assessment corresponded to the combination of agricultural practices resulting in the highest yields *in silico* among the candidate systems both satisfying environmental constraints and meeting environmental targets.

2.2. Main agronomic characteristics of the four innovative cropping systems

The four cropping systems were based on the agronomic strategies described in Table 1 (Colnenne-David and Doré, 2015).

2.3. Experimental trial

Since 2008, the innovative cropping systems have been implemented in a cropping system experiment, located at the AgroParisTech experimental farm at Grignon, in the Ile-de-France region (*i.e.* Paris Basin, N 48.84°, E 1.95°). This site has a deep, homogeneous loamy clay soil (FAO, 1998). Mean annual rainfall, calculated over a 20-year period was about 650 mm per year at this site. The crop immediately preceding this experiment was winter barley and the field had been plowed (30 cm depth). The trial covered a total area of 6.2 ha, divided into large plots (almost 4000 m^2) to facilitate the rational use of farm machinery in conditions representative of those on farms. Due to both the limited area available for the trial and the need for large plots, each system was randomly distributed in a block design with only three replicates. The size of the trial was such that we were unable to grow all of the crops of each crop sequence in each innovative system each year. The interannual variability results were taken into account by sowing three different crops from the crop sequence of each system in the three replicates for the year concerned, for each of the innovative systems (*e.g.* in 2009, winter wheat, winter oilseed rape and spring barley were sown in the three different replicates of the PHEP system). The first full crop sequence covered the 2009–2014 period: five successive crops for the PHEP and L-EN systems (2009–2013), and six for the No-Pest and L-GHG systems (2009–2014).

2.4. Measurements

2.4.1. Calculation of indicators

Assessment of the environmental performance of the cropping systems was based on energy consumption, GHG emissions, C sequestration and various environmental criteria, for real practices in the cropping system experiment. Each environmental indicator was calculated over an entire crop sequence, and expressed on a per hectare and per year basis. Criter® software (V4.0.), based on the Indigo® method and easy to manage, was used to calculate a set of environmental indicators taking values of 1 (worst) to 10 (best), with 7 selected as the target value for the entire crop sequence (Bockstaller et al., 2009; Reau et al., 2012).

2.4.2. Pesticide indicators

Three pesticide indicators provided qualitative information about the volatilization, runoff and leaching into groundwater of pesticides, thereby providing an indication of potential environmental damage. The treatment frequency index (TFI), developed by Gravesen (2003) and widely used to assess cropping systems in France (Ecophyto R & D, 2011; Jacquet et al., 2011), was also calculated, to assess the intensity of pesticide (fungicides, herbicides, insecticides, molluscicides) use. This index takes into account the number of pesticide applications and the amounts applied. For each crop, TFI was calculated as follows: $\mathrm{TFI} = \sum_{\mathrm{T}} {}^{\mathrm{AD_T}}/_{\mathrm{RD_T}}$, where T is the pesticide application, AD is the amount applied per hectare ($l\ ha^{-1}$ or $kg\ ha^{-1}$) and RD is the amount authorized per hectare ($l\ ha^{-1}$ or $kg\ ha^{-1}$) (OECD http://www.oecd.org/site/worldforum/33703867.pdf; Pingault et al., 2009). The recommended doses were those indicated in the E-phy database of the French Ministry of Agriculture (Ephy website, 2014). This indicator describes pesticide use through a single synthetic variable, facilitating