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Research paper

Co-design and *ex ante* assessment of cropping system prototypes including energy crops in Eastern France

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ABSTRACT

Producing biofuels from crops is controversial due to environmental issues and to food security threats linked with the dedication of land to energy crops rather than to food production. The 2009 European Renewable Energy Directive defined the reduction of greenhouse gas (GHG) emissions as an essential requirement for biofuels. Whatever their specific lifespans, energy crops have short- and long-term effects on the following crops, thus requiring assessment at cropping system level, which is rarely done in the literature.

This study aimed at designing and assessing cropping system prototypes (CSP) that include energy crops and food/feed crops in Bourgogne (France), before being implemented in the field (i.e. *ex ante*). CSP were first designed, using a prototyping approach involving scientists and farm advisors, and then *ex ante* assessed, using indicators covering the environment, energy, economic and food issues. They were compared with two cropping systems based on food/feed crops. Lastly, we analyzed the sensitivity of the CSP profitability to several scenarios of crop yields and prices (*i.e.* grain and forage prices for food and feed crops respectively).

CSP including *Miscanthus* x *giganteus* performed better in terms of GHG emissions, energy costs, nitrate losses and pesticide use than CSP that include only annual crops requiring more inputs, but achieved lower profitability and food production capacity. The cropping systems including only food/feed crops frequently achieved higher economic outcomes and food production capacity. Lastly, CSP combining pluriannual or annual energy crops and annual food/feed crops showed satisfactory trade-offs among environmental impacts and food production capacity.

1. Introduction

The production of biofuels from crops is criticized due to its environmental impact [1–4] and to the food security threats [5] linked with the dedication of land to bioenergy rather than to food production. As a result, the European Union enforced sustainability criteria on biofuel production [6]. In particular, biofuels must release 35% less greenhouse gas (GHG), including losses in soil organic carbon (SOC), than the fossil fuels they replace. Moreover, the agricultural feedstock used to produce biofuels must satisfy European regulations aimed at reducing local environmental impacts such as nitrate losses.

Several studies dealing with energy and GHG emissions showed that bioenergy crops, such as giant reed (*Arundo donax*) or *Miscanthus x giganteus,* outperformed food crops [7–12]. However, sensitivity analyses revealed a strong influence of yield estimates on profitability [13], land requirement [11], crop production costs [14], energy yields [15] and GHG emissions per ton of dry matter [15,16]. As observed for other crops, these studies used different methods and data for assessment. For instance, the yield of *Miscanthus x giganteus* (hereafter referred to as *M. giganteus*) either was drawn from experimental data [7,10–12,17,18], or was estimated using models [9,14,19–21]. However, Lesur-Dumoulin et al. [22] reported that *M. giganteus* yields from commercial fields were lower and more variable than those obtained in experiments because of low shoot densities at the end of the establishment year, thus weakening previous assessment results.

In these studies, bioenergy crops were rarely considered as part of a cropping system, which is defined as the crop sequence (*i.e.* the order of apparition of crops in a field over a period of years, for instance corn followed by soybean) and the management techniques (e.g. cultivar choice, insect control strategy) for each crop in the crop sequence [23]. The introduction of a crop and its management in the cropping system indeed generate short-term effects on the following crop and long-term effects [24–26]. For example, after the removal of *M. giganteus*, tilling is lower in the following winter wheat (*Triticum aestivum* L.) crop than in a crop sequence based on annual crops [27]. The use of cereal straw for bioenergy production also has long-term effects, such as a decrease in

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SOC content [28]. Lastly, the introduction of a perennial grass or a Short Rotation Coppice (SRC) after an arable cropping system resulted in increased SOC [29]. Hence, the assessment of energy crops should be improved by taking into account their short-term and long-term effects on the cropping system in which they are included [30].

In the aim of assessing cropping systems including energy crops, a preliminary step of cropping system prototypes (CSP) design is required. There are two main approaches to design innovative CSP [31]: model-based design and a prototyping approach involving experts [32,33]. In the prototyping approach, the use of knowledge from both scientists and farm advisors from extension services in the design step, and the definition of an ambitious goal that the CSP need to fulfil, make it possible to explore a broader range of innovations than in the model-based design [34,35]. To our knowledge, the prototyping approach has not been used yet to design and assess cropping systems combining food/feed crops and energy crops.

This study aimed at designing (by using a prototyping approach) and assessing CSP that include energy crops and food/feed crops in the Bourgogne region (Eastern France), before being implemented in the field (i.e. *ex ante*). Energy crops included dedicated (e.g. *M. giganteus*) and non-dedicated crops, i.e. 'multi-purpose' crops (such as cereals or alfalfa – *Medicago sativa*-), these crops being totally or partly used to produce energy.

2. Materials and methods

2.1. An iterative approach involving design and ex ante assessment steps

We used an iterative method based on a cyclic process of prototyping and assessment [31]. The study area is located in the Bourgogne region (Eastern France) where about 400 ha of *M. giganteus* have been planted on commercial farms since 2009 and where cereals such as winter wheat or barley (*Hordeum vulgare*) and alfalfa used to be grown by farmers (see supplementary material, section 1).

This iterative approach consisted of three sequences, each including a design workshop and an *ex ante* assessment (Fig. 1). The design workshops involved two types of experts:

i) local experts, i.e. farm advisors from extension services and agronomists from technical institutes located in the study area, who provided knowledge about local pedoclimatic conditions and current local cropping systems,
ii) scientific experts, specialized in crops for energy production (including their environmental impacts) and/or on the processes underlying the main goal that CSP need to achieve.

The CSP designed in the workshop during the first sequence were then assessed. During the second design workshop, CSP and the results of their assessment were first presented to the experts. Based on these results, experts modified and refined the CSP. They focused on the CSP including *M. giganteus*. Besides, the mode of *ex ante* assessment was modified: economic scenarios combining low/high input costs, crop prices, and yield assumptions were defined to assess the joint influence of prices and yield variability on economic assessments. Finally, the three sequences presented in Fig. 1 were implemented over three years (from October 2011 to October 2014).

2.2. Description of the design workshops

The design workshops, as previously described by Reau et al. [35,36], included three steps:

(i) Identifying a target, i.e. a set of goals and constraints. At first, the facilitators leading the workshop fixed an ambitious target [37] to stimulate the creativity of the experts in the design of CSP. In accordance with the European Directive on Renewable Energy, the main target identified at the start of the study (sequence 1; see Fig. 1) was a 50% decrease in gross GHG emissions, applied at the cropping system scale. An additional constraint was imposed: no yield losses higher than 33% for food/feed crops compared to the yields obtained for these crops in the study area. As the main goal (i.e. 50% decrease in gross GHG emissions) was achieved for the CSP designed during the first design workshop (sequence 1), facilitators decided to adopt a more ambitious target (a 75% decrease in net GHG emissions) for the second design workshop (sequence 2) to encourage the experts to come up with new ideas. They also refined the target by including constraints on C storage in the soil (in addition to gross GHG emissions), as new knowledge on C storage in the soil under *M. giganteus* was published between the two workshops. This encouraged the experts to design innovative CSP, different from those designed in the first sequence.
(ii) Providing scientific knowledge related to the main target and to the underlying biophysical processes, such that all experts share the same information.
(iii) Designing CSP: facilitators first asked the experts to think individually and give their own ideas about the crops and/or techniques that could be used to reach the target, to provide a basis for the group discussions that followed. Then, they asked the experts to build together CSP including energy crops. The design of CSP involved the choice of a crop sequence, and of the main management practices for each crop and for each between-crop season (i.e. those having a major impact on GHG emissions and water pollution: soil tillage, fertilization and crop protection).

Facilitators suggested to the experts to include the following energy crops, for which it was possible to estimate yields from local expertise and on-farm data: *M. giganteus*, alfalfa, cereals, and corn (*Zea mays*). For cereals, either the whole crop was dedicated to energy production (dedicated crop), or only the straw (whereas grain was used for food or feed). For alfalfa, only the stems were used for energy production, the leaves being used as fodder [38,39]. Cereals (when only the straw was used to produce energy) and alfalfa were therefore considered to be 'multi-purpose' crops. Hereafter, the term 'energy feedstock' will be used to refer both to dedicated energy crops and to the parts of the 'multi-purpose' crops used to produce energy.

2.3. Description of the ex ante assessment of cropping system prototypes

2.3.1. Calculation principles for assessment indicators

The multicriteria assessment of the CSP included four dimensions (Table 1): environmental (referring to gross GHG emissions, SOC sequestration and water quality) [40], economic (profitability for the farmer), energetic (energy costs and energy efficiency), and an assessment of the capacity of the CSP to produce food (food capacity).

In the calculated criteria for the assessment, we took into account all the inputs required for the crop management, from their production until the harvest of the crops. As a result, the effects of fossil fuel displacement of some inputs, internal to the crop management system, were not considered in the GHG balance of the CSP. The inputs included machinery (e.g. tractor), the amounts of fuel, seeds (depending on sowing density), and other types of propagative material (such as rhizomes for *M. giganteus*), fertilizers and pesticides used. The experts provided information about inputs during the design step and, when necessary, two standard databases [41,42] were used to provide additional data. Output data (yields) were estimated taking into account soil, climate, crop sequence and crop management, following the approach described below (see section 3.2).

Assessment results were displayed on a radar chart. For each CSP and each indicator, we calculated a relative score, which was the ratio between the score of the studied CSP and the best score among the other CSP (called 'best value'), for the indicator concerned. The CSP reaching the 'best value' changed according to the considered indicator.

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