A rapid, spatially explicit approach to describe cropping systems dynamics at the regional scale

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1. INTRODUCTION

Agricultural practices and crop performances significantly affect and depend on environmental, social and technical contexts (Ramankutty et al. 2002; Ray et al. 2012; van Vliet et al. 2015). For example, water availability and irrigation technologies allow crop diversification and increase potential yields, but at the same time, the way farmers use water for crop management may determine the state of resources and possibly lead to conflicts with other water users, especially during drought (European Environment Agency 2012; Murgue et al. 2015).

A specificity of agricultural practices is their great spatial and temporal variability. Indeed, farmers make their decisions, both strategic (e.g., crop rotation, irrigated versus rainfed crop production, cultivar earliness) and tactical (e.g., starting/stopping irrigation and its dose), according to the biophysical environment – particularly the spatiotemporal conditions of the soil, weather and plants – as well as the socio-economic context (e.g. prices, regulations). In addition, some management practices, such as irrigation or fertilization, are complex combinations of technical operations at successive dates (e.g. water or fertilizer applications).

Agricultural practices, and specifically their spatial distribution and their dynamics, can affect natural resources, causing environmental issues, such as water scarcity or water pollution (e.g. Glavan et al. 2015; Allain et al., 2018). To address these issues, land managers need spatially explicit information about agricultural practices (e.g. Yunju et al. 2012). Several authors (e.g., Deffontaines 1973; Moss 2000; Scherr and McNeely 2008; Leenhardt et al. 2010; Boiffin et al. 2014) repeatedly mention the need to improve methods to describe agricultural practices at the regional scale, i.e. on areas where exhaustive surveys of farms are impossible (typically around 100 km² and above). A consistent approach would be useful for exploring land management practices and integrating them at various spatial and temporal scales. This would help formalize the knowledge that farmers and other land managers use to make their decisions (Sarangi et al. 2004; Macé et al. 2007; McCown 2012). To be reliable, this approach should obtain knowledge about all components of "cropping systems".

A cropping system is defined for a uniformly managed spatial unit as a sequence of crops and the management system for each crop in the sequence. The crop management system is the set of technical operations applied to the crop, for all management practices: soil tillage, cultivar choice, fertilization, weed and pest management, irrigation, etc. (Sebillotte 1990). Describing the spatial distribution and the dynamics of cropping systems at the regional scale to address natural resource management issues needs to consider (i) biophysical and socio-economic conditions driving their spatial distribution, hereafter called *location factors* (Clavel et al. 2011; Temme and Verburg 2011); and (ii) the *decision rules,* which determine the nature and timing of each technical operation.

Describing the spatial distribution of cropping systems at the regional scale remains a major scientific challenge (Therond et al. 2009; Leenhardt et al. 2010; Rizzo et al. 2013; Murgue et al. 2016). Recent improvements in satellite imagery, the increased availability of harmonized censuses and surveys at large scales have contributed to the development of spatially explicit cropland databases. For example, remote-sensing-based databases (Bégué et al. 2015; Waldner et al. 2015a) and periodic surveys such as the European Land Parcel Identification System (LPIS) (Sagris 2013), the LUCAS database (Temme and Verburg 2011), the French TerUti database (Xiao et al. 2014), and the Farm Accountancy Data Network (Vitali et al. 2012) provide improved support for describing and modeling crop sequences. The generic character of these databases allows using them for many purposes in different domains and at different levels of analysis (Murgue et al. 2016). However, they have a major limitation: the static perspective adopted for crop management systems is not appropriate for analyzing the dynamic interactions between technical operations, weather conditions and natural resource conditions (Ruiz-Martinez et al. 2015; Murgue et al. 2016). Studies based on these data have addressed the crop management component of cropping systems only loosely (Martínez-Casasnovas et al. 2005; Mignolet et al. 2007; Steinmann and Dobers 2013; Sahajpal et al. 2014; Kollas et al. 2015), for example representing average practices (Therond et al. 2011) or fixed-calendar scheduling (Dupas et al. 2015).

Overall, we identify three major obstacles that limit a complete description of cropping systems with such databases. First, available land cover maps provide insufficient spatial continuity and temporal depth to properly describe crop sequences (Fuchs et al. 2013; Xiao et al. 2014). Second, a lack of information about crop management exists; it is generally addressed by using land cover as a rough proxy (e.g., Verburg et al. 2009; Houet et al. 2014; Zimmermann et al. 2016). Third, only a few methods can represent the dynamic adaptation of crop management to pedoclimatic conditions (Houet et al. 2010; Hutchings et al. 2012; Constantin et al. 2015). The most advanced are based on crop management decision rules formalized with classic *IF [Indicator] [Operator] [Threshold] THEN [Action1] ELSE [Action2]* rules (Bergez et al. 2001; McCown 2012).

Formalizing decision rules and coupling them with crop models enables simulating dynamics of crop management systems and their effects on the soil-crop system dynamics and possibly on water resources. For example, irrigation decision rules influence water withdrawals, which modify the water resource (Clavel et al. 2012; Murgue et al. 2014). The challenge lies in describing decision rules associated with cropping systems within a region in a way that accounts for the potentially great variability in individual decision-making processes (Nesme et al. 2005; Leenhardt et al. 2010).

To describe the spatial variability and dynamics of cropping systems, it is critical to enrich the information provided by generic data sources with local knowledge obtained mainly through interviews, surveys or local databases (Marie et al. 2008). Local knowledge is crucial to capture information related to farmers' decisions, i.e. location factors and crop management decision rules. This knowledge is largely implicit, however, and consequently difficult to access (Aubry et al. 1998; Tress et al. 2003; Toffolini et al. 2015; Murgue et al. 2016). Interviews with farmers remain the main approach for obtaining this knowledge (Marie et al. 2008; Debolini et al. 2013; O'Keeffe et al. 2015). However, an exhaustive survey of all farmers in a region can easily become excessively time-consuming (see examples in Maton et al. 2007; Schaller et al. 2012).

Rapid surveys can be limited to easily observable features (Biarnès et al. 2009) or performed on stratified samples based on pre-defined farm typologies (Joannon et al. 2006; Murgue et al. 2016). Despite these simplifications, collecting farm survey data to describe the spatial distribution and dynamics of cropping systems remains time consuming. For example, Murgue et al. (2016) interviewed 27 farmers to describe their decision rules in detail (indicators and thresholds) for maize and other regionally relevant crops in an 840 km² watershed (downstream area of the Aveyron River, southwestern France). Each interview lasted approximately half a day. In total, the interviews took more than 13 working days, plus the processing time to formalize all crop management system decision rules (≈2 months) (Hipolito 2012). Although the study described spatial distribution of cropping systems with location and decision rules, the process was resource-consuming and therefore would be difficult to repeat for multiple and large study areas.

This article presents a simple, rapid approach to describe spatial distribution of current cropping systems at the regional scale in a way that considers their dynamic dimensions and thus can be used for simulation purposes. It builds on the study by Murgue et al. (2016), which modeled irrigation practices at the watershed scale. The approach we adopted to describe the cropping systems and their spatial distribution is a low-data method (sensu Therond et al. 2011), i.e. based on expert knowledge and easy-to-collect regional crop management information. Expertise collection rested on the "key informant" approach originally described by (Tremblay 1957) where key informants are considered as experts having a perception grounded in theory, yet attained as a result of deep understanding, practice and interaction with the subject matter (Twongyirwe et al. 2018). We hypothesized that key informants, in our case local extension agents, have sufficient knowledge to describe location factors and decision rules of cropping systems at the regional scale and identify their most relevant characteristics at the field scale. We evaluated this approach in two large areas in southwestern France, first in the Tarn River area and then in the Adour River area. To assess the reliability of our approach to model the cropping systems and their spatial distribution, we used a multi-agent, spatially explicit model that simulates their effects on water withdrawals, and then compared the simulated water withdrawals to observed ones.

2. MATERIALS AND METHODS

2.1 Case studies and available data

Focused on the interactions between irrigation and water-deficit issues, this study explored irrigation-management practices in two study areas in the Adour-Garonne River basin in southwestern France (116 000 km², Midi-Pyrénées region), which experiences a chronic imbalance between water resources and water needs during the low-water period, which occurs mainly during summer (Debril and Therond 2012; Mazzega et al. 2014). The first area (2 952 km²) is located in the downstream area of the Tarn River, one of the main tributaries of the Garonne River. This area is influenced by a Mediterranean climate, with high temperatures in summer and heavy rainfall events in autumn and spring. Of note, this area is contiguous with the Aveyron watershed, the above mentioned case study by Murgue et al. (2016). The second area (1 446 km²) is located in the upstream area of the Adour River, which drains the northern slopes of the French Pyrenees. Recent statistics highlight that it has the highest irrigation water withdrawals in the Adour River basin (OEBA 2015). Its climate is oceanic, with relatively warm and humid weather in summer and heavy rainfall events in winter. The two main soil types in each study area are (i) alluvial and hydromorphic loamy silt soils, mainly associated with fluvial terraces, and (ii) calcareous clayey soils, which predominate elsewhere (Fig. 1 A and B).

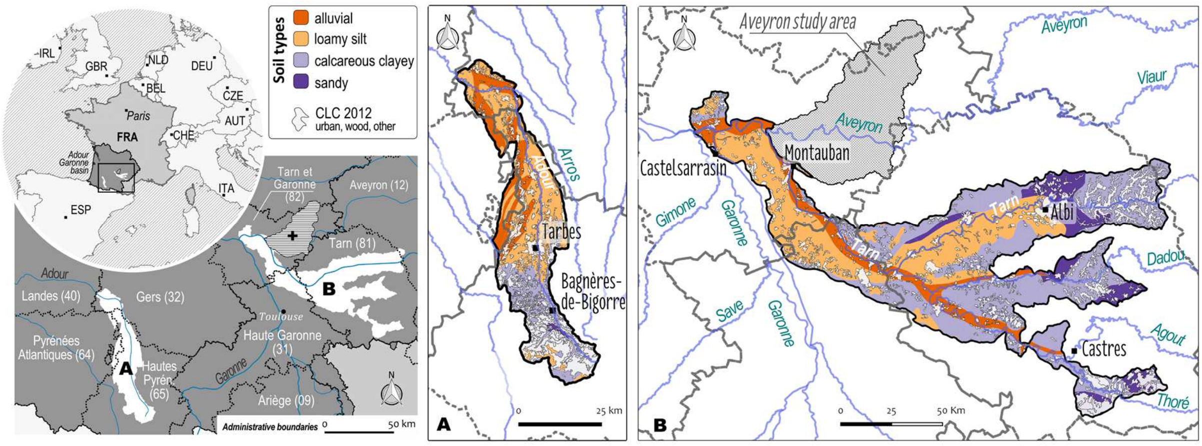

Figure 1. Locations and characteristics of the study areas (A) Adour and (B) Tarn, which is closer to the Aveyron study area of Murgue et al. (2016) (gray). Non-agricultural areas (white) on the soil maps represent the following CORINE Land Cover classes for 2012: urban, woods, wetlands, and water bodies.

As for any area in France, generic databases are available to map the main attributes of the study areas (Murgue et al. 2016). For example, the "Land Parcel Identification Systems" (LPIS) is a georeferenced database to be developed by each member state of the European Union to control annual Common Agricultural Policy (CAP) subsidies. It stores the land cover information (nature and area) of each CAP islet of each farmer concerned by these subsidies (Inan et al. 2010). We used the French LPIS database (for 2006-2012) to (i) map the main annual crops and spatial distribution of fields (ASP 2012), (ii) retrace crop sequences at the field scale, and (iii) identify fields that were declared as irrigated at least once from 2007-2009. Of note, LPIS no longer collected irrigation-related data after 2009. The French LPIS mapping unit is a “farmer’s block” or “Common Agricultural Policy islet”, which corresponds to one or more aggregated contiguous agricultural land parcels (Sagris 2013; Murgue et al. 2016). We also used the CORINE Land Cover database for 2012 (EEA 2015) to complete the land-use map for orchards, typically underrepresented in LPIS, and to map non-agricultural land cover (i.e., forest and urban). Representing 55% of the total area, arable land dominates in both study areas, but includes different percentages of irrigated area: 28% in the Tarn area and 39% in the Adour area (Table 1). Additional information about cropland composition was obtained from the general agricultural census performed by the French Ministry of Agriculture (Agreste 2010) and freely available at the Local Administrative Unit 2 level, corresponding to a French municipality (Eurostat 2015).

Table 1. Main characteristics of the two study areas (for 2012). Source: Land Parcel Identification System (LPIS) and CORINE Land Cover data. The number of crop fields was obtained from LPIS data after processing (see details in Leenhardt et al. (2012))

Characteristic	Tarn	Adour
Area (km²)	2 950	1 446
Estimated Farmed Agricultural Area (FAA, ha)	160 961	79 359
Percentage of FAA in total area	55%	55%
Estimated irrigable FAA (ha)	44 595	30 723
Percentage of FAA irrigable	28%	39%
Farms	4 184	2 671
Percentage of irrigated farms	36%	41%
Crop fields	85 484	45 716

We obtained climate data from the SAFRAN database (Vidal et al. 2010) and soil types from the French Geographic Soil Database at a scale of 1:1 000 000, which represents the French portion of the European Geographic Soil Database (King et al. 2005; Antoni et al. 2007). Finally, we used water withdrawal data provided by water users through an annual mandatory report to the Adour-Garonne Water Agency (AEAG 2015). For each water user, these data provide the total amount of water withdrawn at each “withdrawal point”. The locations of only a few points are known precisely; most are approximated as the centroid of the municipality containing the withdrawal point. Since the boundaries of the two study areas did not overlap with municipality boundaries, we multiplied the reported withdrawn water volumes by the percentage of the municipal area located within each watershed, to estimate water withdrawals in each study area.

2.2 Key informant interviews

To identify key informants, namely experts with knowledge about the spatial distribution and management of the main irrigated crops, we first interviewed shortly the managers of the agro-environmental department of the extension service of each area (30mn each). They designated the technicians of agricultural extension services who could serve as key informants regarding the main crops of the studied areas (Table 2). We conducted four semi-structured face-to-face interviews, lasting approximately 2.5 hours each, to deal with the two irrigated crop classes for which the most water for irrigation is withdrawn: maize and orchards. Three of the four interviews involved two key informants at the same time.

Table 2. Description of key informants (by expected expertise and study area) and interviews (by type, number of people interviewed and duration).

Key informants			Interviews		
Expected expertise	**Tarn**	**Adour**	**Telephone**	**Face-to-face**	**Duration**
Maize production and irrigation practices	2	2		2	320 min
Orchards and drip-irrigation practices	2	-		1	120 min
Cash crops	1	-		1	140 min
Vineyards	1	-	1		20 min
Seed production and legumes	1	-	1		20 min
Pastures and alfalfa	1	-	1		20 min
Total	8	2	3	4	640 min

We designed the interview script to focus on the question: "How is irrigation managed for the main crops in the study area?" The interview was composed of four steps: (i) identify the main crops in the target area, (ii) create a list of land use classes for each crop (e.g., for maize: rainfed, irrigated, silage, seed), (iii) describe water consumption (i.e., volumes per period) for the main crops irrigated within irrigated crop classes and (iv) describe indicators and thresholds necessary to define IF-THEN crop management decision rules and location factors used to define location rules.

Interviews were supported by intermediate objects to (i) summarize existing knowledge to highlight and help fill information gaps and (ii) mediate between the researchers and local key informants (Vinck 1999; Buller 2009). The rationale was to facilitate elicitation of decision rules that underlie crop management practices. Finally, these intermediate objects were used to obtain easy-to-formalize, spatially explicit answers, since they provide a framework to pre-process key informants' discourses into an input format for the simulation model.

The intermediate objects were a map, a table and several diagrams. The map was used at the beginning of the interview to clarify watershed boundaries (Fig. 1 A and B), which differ from those of the administrative unit at which the interviewees work: the *Département* also called NUTS 3 (Eurostat 2015). The table listed the main crops identified from analyzing census data (for 2010) and LPIS and CORINE Land Cover maps (both for 2012). The diagrams (Fig. 2) were designed to help interviewees depict management practices for each main irrigated crop in the region. They were structured around a simplified calendar that explicitly required specifying indicators and threshold values that farmers are expected to use to start or stop sowing, irrigation and harvest. To identify cropping systems associated with each crop, we asked key informants if the values identified for standard management of the crop could vary in space or according to location factors (e.g. crop sequence, soil type, irrigation equipment). For example, key informants indicated that winter wheat can be irrigated if it occurs in the same sequence as maize, otherwise it is rainfed. We also asked key informants to describe an average year and then identify possible adaptations to infrequent conditions (e.g., humid or dry seasons). During the process, we invited key informants to rely on their own field experience of crop management practices rather than on the advice they usually give to farmers.

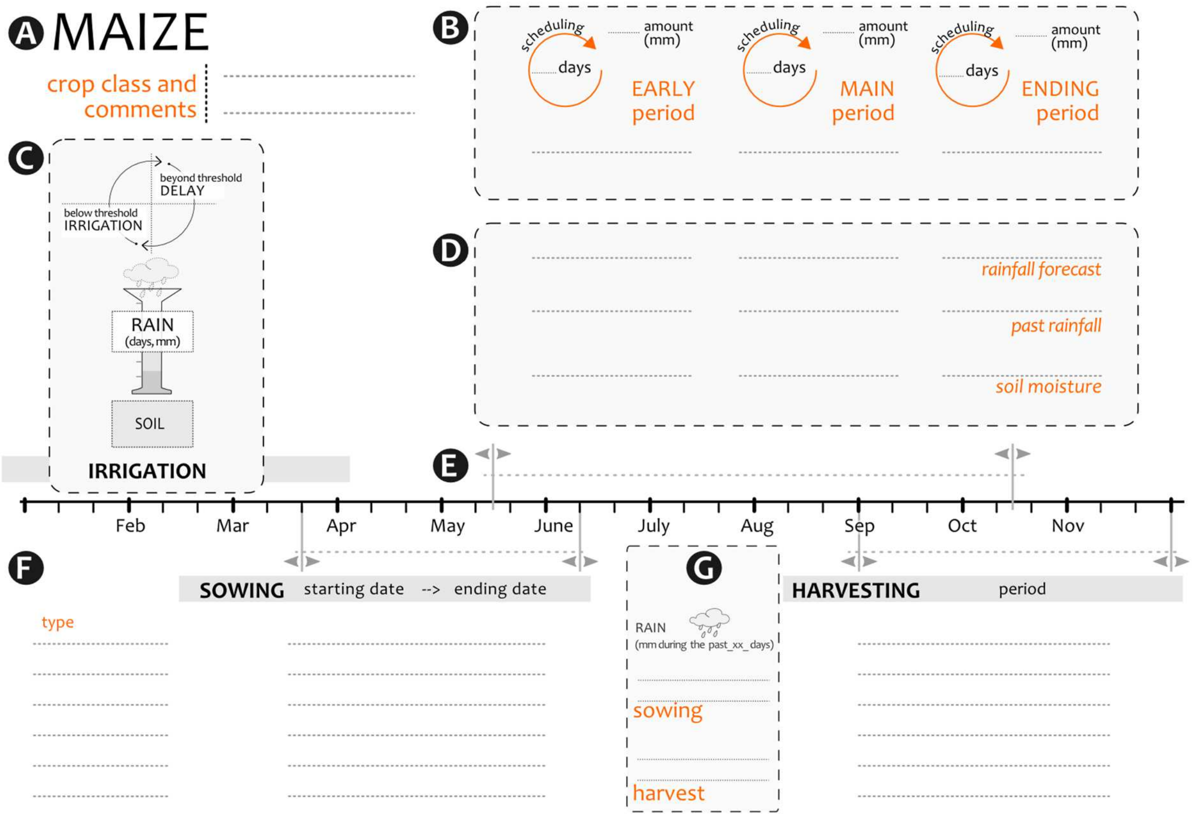

Figure 2. Example of a diagram used during key informant interviews. Interviewees were asked (A) to specify the crop class and (B) to quantify irrigation scheduling (number of days between two applications) during the most relevant periods. Then, after (C) a quick reminder of the modeling approach, they were asked to list (D) indicators (e.g., rainfall, soil moisture) and the associated thresholds farmers use to manage irrigation during (E) the irrigation season. Similarly, the timeline was used to frame (F) the scheduling of sowing and harvesting, for which interviewees were asked to set (G) indicators and thresholds underpinning the decision rules. Source: English translation of the original in French.

These face-to-face interviews were supplemented with phone interviews to obtain missing information about specific crops (e.g., legume, pastures, vineyards - see Table 2). Phone interviews (approximately 20 minutes each) began with the same short introduction as the full interview, which was followed by a short list of questions about crop management decision rules and expected irrigation volumes for a standard cropping season. The interviewer recorded answers on the intermediate objects (tables and diagrams) described previously.

Both types of interviews were transcribed into a text editor in preparation for analysis. We processed the local information by grouping all details provided for each crop and cropping system during the interviews to address possible differences among key informants, especially those with different fields of competence, and to formalize and encode a first draft of the decision rules.

Altogether, from interviews to the first draft of decision rules, the key informant approach required approximately 260 working hours for the two study areas.

2.3 Modeling cropping systems and their spatial distribution

Based on the information collected from interviews, we modeled spatial distributions of cropping systems in each study area in three steps. First, we addressed the two components of cropping systems, namely the crop sequences (step 1) and the decision rules of crop management (step 2). Then, we coupled the dynamic decision rules with the location factors (step 3).

Step 1. Describing crop sequences using real data

Our objective was to define sequence types to infer irrigation management rules. First, we processed the 2006-2012 LPIS data (simplifying the crop labels slightly to perform an initial grouping). This allowed us to identify the real crop sequences observed in all farmers' blocks (see details in Leenhardt et al. 2012). Since this list of sequences was too large to manage easily, we created a typology of crop sequences useful for dealing with crop management decision rules. For this, each type of crop sequence was defined by the proportion of each crop in the duration of the sequence, regardless of their order. For example, Maize-Maize-Maize-Soybean-Wheat-Maize belongs to the sequence type "maize, rotation", in which maize occurs more often than any of the other crops.

Second, we adapted the generic LPIS crop classes using the information from interviews about main local crops. We aggregated crop classes covering small areas (e.g., different types of set-aside land) or those with similar water use and irrigation practices (e.g., grain legumes and protein crops). We disaggregated crop classes into new sub-classes when key informants indicated the need to differentiate irrigation management practices (e.g. silage maize vs. grain maize).

Step 2. Modeling crop management systems using the information retrieved

Dynamics and locations of crop management systems were modeled using rules developed from information collected during interviews. We used information about indicators and their threshold values to formalize sowing, irrigation, and harvest management rules for each crop. We used information about location factors to develop location rules. For example, the crop sequence type was identified as a location factor: wheat is irrigated only if it occurs in a sequence including maize, but not if it occurs in a rainfed sequence type (e.g., cereal-sunflower). The location rules were then used to assign a crop management system (described as a set of decision rules) to each combination of [crop sequence type] × [soil] × [irrigation equipment].

Step 3. Defining the spatial distribution of cropping systems

Cropping systems were assigned to each land parcel in each farmer's block according to the following procedure. The soil type, crop sequence type, irrigation status and irrigation equipment of land parcels were characterized using GIS. The dominant agricultural soil type of each farmer's block from the 1:1 000 000 soil database was assigned to each of its land parcels. If the original LPIS crop class observed on a given land parcel was divided into new classes during step 2, one of these new classes was assigned to the land parcel according to location factors such as the soil type, crop sequence or crop area of the farm it belonged to, while respecting, for each study area, the proportions of these new classes observed in the 2010 agricultural census (Agreste 2010). We assigned the crop sequence of each land parcel to a crop sequence type (defined in step 1) using the Dice percentage similarity index (Dice 1945). Irrigation status of a land parcel was determined using 2007-2009 LPIS data. We assumed that land parcels were potentially irrigated, i.e. equipped for irrigation, if the farmer's block they belonged to was irrigated at least once during those years. Crops that can be managed either with or without irrigation were assumed to be potentially irrigated only if they occurred in a farmer's block equipped for irrigation. Due to a lack of local information about the relative frequencies of types of irrigation equipment and the location factors that influence them, we assigned the equipment used most in the area (travelling gun sprinkler) to each potentially irrigated farmer's block.

Finally, a crop management system was assigned to each land parcel in each farmer's block in which the crop occurred according to the observed combination of [crop sequence type] × [soil] × [irrigation equipment], using the table constructed in step 3.

2.4 Evaluating the approach

Evaluating our approach was challenging: because it was developed to compensate for the relative lack of cropping system data, it used all the data available to formalize and spatialize the cropping systems, leaving no data for classic "observed vs. simulated" evaluation. We therefore evaluated the approach indirectly. We used the cropping system information retrieved from our approach to parameterize a model able to simulate irrigation withdrawals and compared simulated withdrawals to withdrawal data obtained from the Adour-Garonne Water Agency (AEAG). Since AEAG data were annual data only, we also verified that, for each cropping system, the simulated withdrawal dynamics were consistent with key informants' descriptions of irrigation starting and ending dates. Irrigation withdrawals were chosen as an evaluation indicator because the simplified survey of crop management practices focused on irrigation and only secondarily on sowing and harvesting. The model used was chosen for its ability to account for all components of the cropping system: the observed crop sequences retrieved from the generic data sources, the decision rules and the location factors identified from the key informant interviews. This indirect way to evaluate the reliability of a modeled spatial distribution of cropping systems was previously used by Murgue et al. (2016).

For simulating water withdrawals, we used the agricultural module of the MAELIA multi-agent and spatially explicit simulation platform (Gaudou et al. 2013; Therond et al. 2014; Mazzega et al. 2014; http://maelia-platform.inra.fr/). This agricultural module, fully described by Murgue et al. (2014), combines a soil-crop model and a farmer agent model. The former predicts daily soil water balance based on rainfall, evapotranspiration, soil water content and crop development stage (Constantin et al. 2015). The latter applies farmers' decisions using crop management decision rules. Virtual farmer agents check, every day and for each land parcel, whether thresholds encoded in management rules have been reached or exceeded and, if so, perform the corresponding technical operation(s). Note that since the hydrological and normative modules of MAELIA were deactivated, virtual farming agents have access to unlimited water resources.

The modeled cropping systems, i.e. observed crop sequences purposely simplified (step 1), along with the decision rules (step 2) and the location rules (step 3), were used to parameterize the agricultural module of MAELIA. Through the multi-agent structure of MAELIA, this module (soil-crop and farmer agent models) was run independently for each land parcel in each farmer's block on each farm in each study area. During a simulation, the model reads through the crop sequence each year to find the crop grown, then associates the crop with its management system (i.e., the set of IF-THEN rules) as a function of the crop sequence type, soil and irrigation equipment, based on the table constructed for this purpose. The simulation ran from 2003, an extreme drought season, to 2012, thus covering the period for which LPIS data were available to reconstruct crop sequences (i.e., 2006-2012). Crop sequences observed from 2006-2012 were replicated to cover the previous years without LPIS data (2003-2005).

Given the many fields simulated (Table 1) and their multiple interactions, our first objective was to reproduce the interannual dynamics of total withdrawal recorded in the AEAG database.

3. RESULTS

3.1 Cropping systems

Twenty-three crops out of the 29 recorded in the LPIS are cultivated in the two study areas (Fig. 3 and 4, columns 1 and 2). For the Tarn area, we identified 21 330 crop sequences, which were grouped into 22 sequence types (Table 3). For the Adour area, LPIS analysis identified 7 163 crop sequences, which were grouped into 18 sequence types (Table 4). Figure 5 and Table 7 report the percentages and location factors used to determine the "new" crop classes in both areas, i.e. those different from the original LPIS. The original LPIS "maize" class was first divided into silage maize and grain maize according to a decision tree based on the percentages of maize and pasture area in the farm agricultural area (Table 5). Next, the grain maize class was divided into two classes of earliness depending on the crop sequence and the soil in the land parcel (Fig. 5). The “other cereals” and “orchards” LPIS classes were also divided into new classes according to crop sequence and soil type location factors. For example, in the Tarn area, kiwifruit orchards were randomly located on 25% of the land parcels grown continuously in orchards (according to LPIS) and situated on alluvial soils. This approach resulted in 18 crop classes, 14 of which can be irrigated, in the Tarn area (Fig. 3, column 4) and 14 crop classes, 11 of which can be irrigated, in the Adour area (Fig. 4, column 4).

Figure 3. Definition of the crop classes at the regional scale in the Tarn area. Crop classes are irrigated (••), seldom irrigated (•) and exclusively rainfed (°). Absent crops from the original LPIS list were not reported. The second column shows the original Land Parcel Identification System (LPIS) label and, in parentheses, the label corresponding to the initial grouping of classes performed before crop sequence processing and used in Table 3.

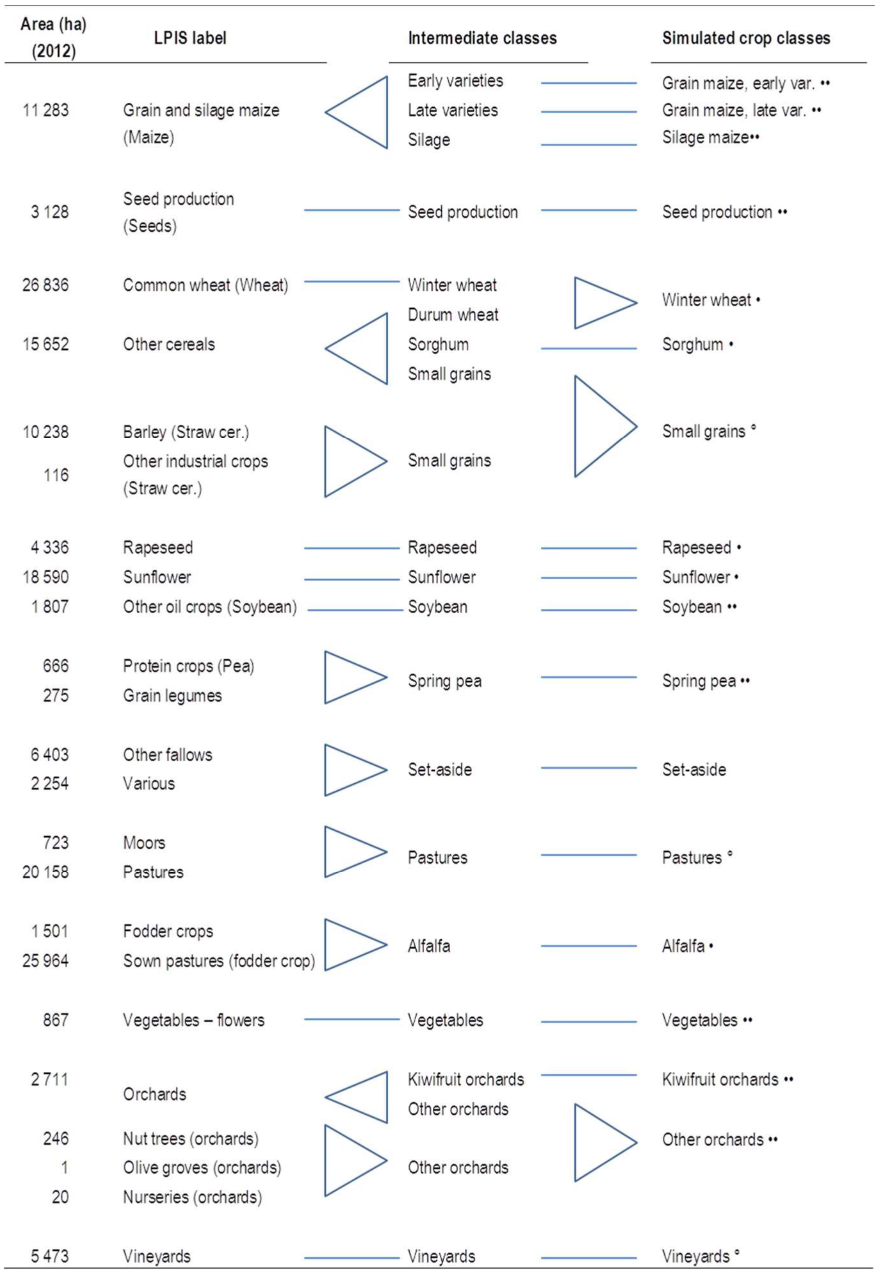

Figure 4. Definition of the crop classes at the regional scale in the Adour area. Crop classes are irrigated (••), seldom irrigated (•), or exclusively rainfed (°). Absent crops from the original LPIS list were not reported. LPIS = Land Parcel Identification System. The second column shows the original Land Parcel Identification System (LPIS) label and, in parentheses, the label corresponding to the initial grouping of classes performed before crop sequence processing and used in Table 4.

Area (ha) (2012)	LPIS label	Simulated crop classes
32 070	Grain and silage maize (Maize)	Grain maize, early var. •• Grain maize, late var. •• Silage maize ••
3 574	Common wheat	Small grains •
690	Barley	
996	Other cereals	
12	Other industrial crops	
133	Protein crops	Soybean ••
7	Grain legumes	
375	Other oil crops	
487	Vegetables – flowers	String beans ••
32	Orchards	Orchards ••
7	Nut trees	
0	Olive groves	
3	Nurseries	
1 307	Rapeseed	Rapeseed •
1 944	Seed production (Seeds)	Seed production ••
1 196	Sunflower	Sunflower•
194	Fodder crops	Alfalfa •
6 765	Sown pastures	
12 514	Moors	Pastures °
11 422	Pastures	
2 723	Other fallows	Set-aside
916	Various	
1 924	Vineyard	Vineyards °

Table 3. Crop sequence types for the Tarn area (first column). Each sequence is described by the dominant crop classes, its duration (each crop representing one year), and the frequency with which each crop occurs. For example, "Maize, rot" (rot = rotation) is a 6-year sequence with maize (silage or grain, early or late variety) in 3 out of 6 years, soybean, wheat and another cereal. For monocropping (mc) and perennial production, the crop is only listed in the second column. Note that crops in a sequence that can be irrigated or rainfed are managed differently. Crop names come from the Land Parcel Identification System (original label, or labeled after the initial grouping – see Fig. 3).

Sequence type	Sequence Crop 1	Crop 2	Crop 3	Crop 4	Crop 5	Crop 6	Crop 7
IRRIGATED							
Maize, mc	Maize						
Maize, rot	Maize	Maize	Maize	Soybean	Wheat	Other cer	
Cereals - Soybean	Wheat	Other cer	Soybean				
Cereals	Wheat	Other cer					
Alfalfa - Maize	Fodder crop	Fodder crop	Fodder crop	Maize			
Seed production, mc	Seeds						
Seed production, rot	Seeds	Seeds	Wheat	Other cer			
Vegetables	Vegetables						
Orchards	Orchards						
RAINFED							
Maize, rot	Maize	Maize	Maize	Soybean	Wheat	Other cer	Straw cer.
Cereals - Soybean	Wheat	Other cer	Straw cer.	Soybean			
Cereals	Wheat	Other cer	Straw cer.				
Cereals - Sunflower	Wheat	Other cer	Straw cer.	Sunflower			
Cereals - Rapeseed	Wheat	Other cer	Straw cer.	Rapeseed			
Vegetables	Vegetables						
Set-aside	Set-aside						
Alfalfa - Cereals	Fodder crop	Fodder crop	Fodder crop	Straw cer.			
Alfalfa - Maize	Fodder crop	Fodder crop	Fodder crop	Maize			
Mix	Small grain	Pea	Sunflower	Soybean	Seeds	Alfalfa	Set-aside
Grassland	Pastures						
Orchards	Orchards						
Vineyards	Vineyards						

Table 4. Crop sequence types for the Adour area (first column). Each sequence is described by the simplified dominant crop classes, its duration (each crop representing one year), and the frequency with which each crop occurs. For example, “Maize, rot” (rot=rotation) is a 5-year sequence with maize (silage or grain, early or late variety) in 3 out of 5 years, soybean and a small grain cereal crop. For monocropping (mc) and perennial production, the crop is only listed in the second column (Crop 1). Since the grouping of crops in the Adour area was relatively simple, we used the labels of the simplified crop classes (Fig. 4) to name the crops (except for maize).

	Sequence					
Sequence type	**Crop 1**	**Crop 2**	**Crop 3**	**Crop 4**	**Crop 5**	**Crop 6**
IRRIGATED						
Maize, mc	Maize					
Maize, rot	Maize	Maize	Maize	Soybean	Small grains	
Alfalfa - Maize	Alfalfa	Alfalfa	Alfalfa	Maize		
Seed production, mc	Seeds					
Seed production, rot	Seeds	Seeds	Small grains			
String beans	String beans					
Orchards	Orchards					
RAINFED						
Maize, rot	Maize	Maize	Maize	Soybean	Small grains	
Cereals	Small grain					
Cereals - Sunflower	Small grain	Sunflower				
Cereals - Rapeseed	Small grain	Rapeseed				
Set-aside	Set-aside					
Alfalfa - Cereals	Alfalfa	Alfalfa	Alfalfa	Small grains		
Alfalfa - Maize	Alfalfa	Alfalfa	Alfalfa	Maize		
Mix	Sunflower	Soybean	Seeds	Alfalfa	pastures	Set-aside
Grassland	Pastures					
Orchards	Orchards					
Vineyards	Vineyards					

Table 5. Distribution of the Land Parcel Identification System maize class into grain and silage classes based on location factors (percentages of maize and pasture in the farm area). This model was used for both the Tarn and Adour areas.

Location factors		Distribution of the LPIS maize class into grain and silage classes	
% of maize in farm agricultural area	% of pasture in farm agricultural area	Grain maize	Silage maize
< 30%	–	75%	25%
> 30%	< 10%	100%	0%
	10-35%	50%	50%
	> 35%	100%	0%

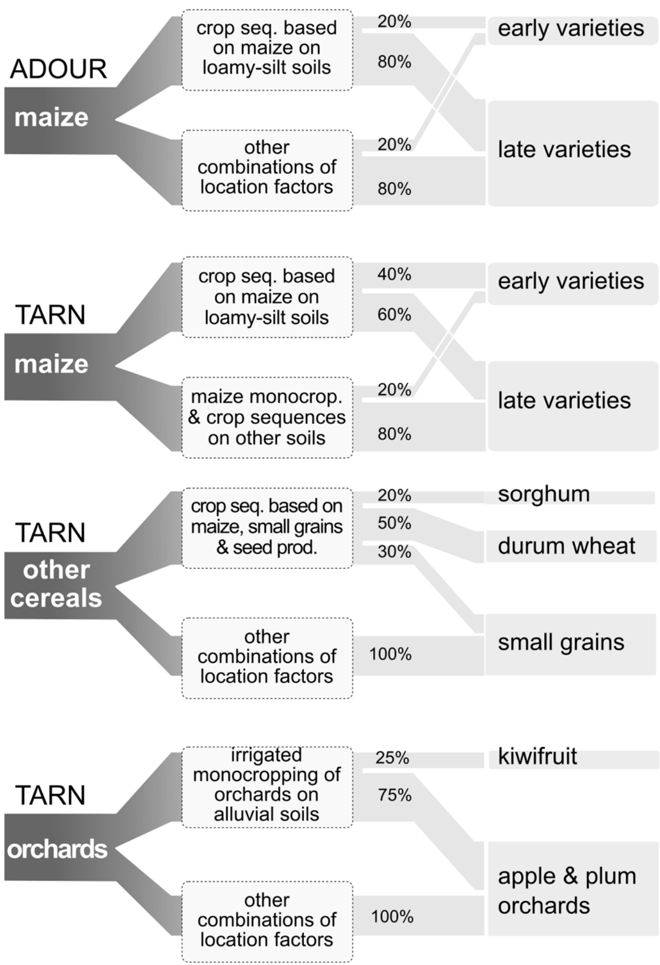

Figure 5. Procedure used to develop detailed crop classes from original Land Parcel Identification System (LPIS) classes, as specified by key informants (cf. step 1 of the crop system modeling). The diagram presents the original LPIS class (col. 1), the location factors (col. 2) and percentages (col. 3) used to divide LPIS classes, and possibly recombine them, into new crop classes (col. 4). Here, "maize" is only grain maize. This procedure was applied to one area each in the Adour and Tarn watersheds, France.

Based on the irrigated and rainfed areas of each crop derived from LPIS irrigation data for 2007-2009 (Fig. 6), maize was the most extensively irrigated crop in both areas. For the Adour area, we estimated that ≈70% of maize area was irrigated, whereas the key informants estimated that 75% was irrigated. For the Tarn area, we estimated that 93% and 82% of late and early maize varieties, respectively, were irrigated, whereas the key informants estimated that 100% of each was irrigated (Fig. 6). As for location factors of cropping systems, the key informants mainly emphasized soil water-holding capacity (i.e., the greater the clay content, the higher and less frequent the irrigation) and irrigation equipment (e.g., pivot irrigation has lower doses and higher frequency than sprinkler irrigation).

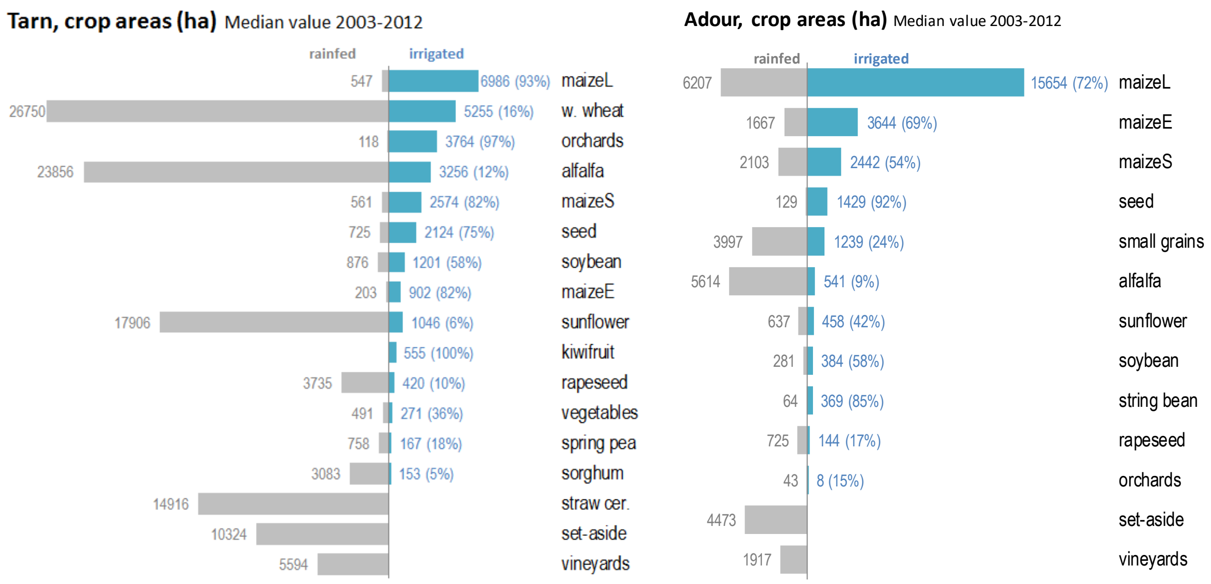

Fig. 6. Median rainfed and irrigated crop areas (ha) for the period simulated (2003-2012) in the two study areas. Values in parentheses indicate the percentage of total crop area that was irrigated. Maize is divided into silage (maizeS), early (maizeE) and late (maizeL) varieties, in addition to seed production.

3.2 Simulated water withdrawals at the regional scale

Median annual withdrawals for 2003-2012 reported by AEAG were 39.7 and 42.7 hm^3 for the Adour and Tarn areas, respectively, while MAELIA predicted 37.7 and 40.4 hm^3 (Fig. 7), respectively (under-predicted by 5%). The model simulated well withdrawal dynamics among years (Fig. 7). Predictions for the Tarn area ranged from 16% below (in 2011) to 11% above (in 2009) observations. Predictions were less accurate for the Adour area, especially for 2003-2005; for 2006-2012, they ranged from 14% below to 11% above observations. Less accurate predictions in the Adour area for 2003-2005 may have been influenced by the lack of LPIS crop data before 2006 and by the quality of the AEAG data for withdrawn volumes. Notably, AEAG data for the Adour area in the earlier years were mostly estimates based on farm irrigated area, while those in the later years were mostly measurements. This factor could be the most important, since the AEAG obtained measured withdrawals from an earlier date in the Tarn area, for which predictions were more accurate.

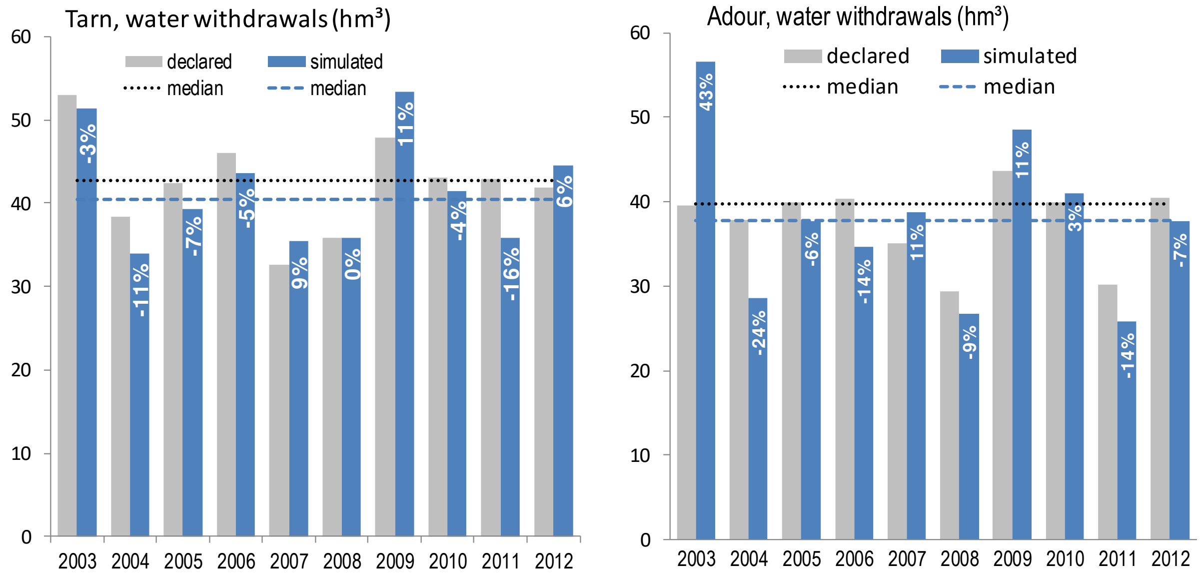

Fig. 7. Comparison of water withdrawals for irrigation declared to the water agency by irrigating farmers and predicted by the agricultural module of the MAELIA platform.

4. Discussion

In this article, we present a method to model the current cropping systems and their spatial distribution at the regional scale. Similar approaches for the same objective, based on a few local key informants, were used to describe the influence of agriculture on landscape management (Galli et al. 2010) and to identify strengths and weaknesses of extension services (Debolini et al. 2013). The discussion below addresses the (i) strengths, (ii) limits, (iii) replicability and genericity and (iv) evaluation of our approach to describe cropping systems at the regional scale.

Strengths. Our approach, based on generic data sources, key informant interviews and decision modeling, allowed us to describe current cropping systems at the regional scale, not only as a static picture but as dynamic systems. The generic data sources allowed the description of crop sequences. Key informants allowed us to directly access average farmers' strategies: we assumed that extension agents would have a wide view of crop management systems and could identify average decision rules and potential local and individual adaptations. Their integrated vision of the study area helped us to avoid the interpretation difficulties that occur in detailed surveys of agricultural management practices performed at the farm level: great heterogeneity among farmers and bias resulting from complying with regulations or from small samples (Schott et al. 2014). The ability to obtain extensive coverage of the study areas from only a few interviews was facilitated by the fact that French extension services are generally organized to operate with relatively few agents. In this regard, the help of the two managers was crucial. The design of targeted intermediate objects (maps, tables and diagrams) also helped structuring the interviews to obtain the missing data in the two study areas. When evaluating this approach with MAELIA's agricultural module, we observed a similar ability to simulate water withdrawals as in the previous study in the nearby Aveyron watershed (Murgue et al. 2016). Our approach, using local knowledge of key informants to formalize location and crop management rules, performs as well as the previous approach: the same order of magnitude of differences between simulated water withdrawals and AEAG withdrawals in the present study as in Murgue et al. (2016). Besides, our simplified approach is more efficient since it enabled us to describe crop management systems at the regional scale on six times as many fields as in the Aveyron study (Murgue et al. 2016), in approximately one-fourth of the time required in this previous study.

Limits. The limits of our approach are closely related to the quality of the generic data and the local knowledge used.

First, the irrigated status of land parcels appears as probably poorly estimated, as revealed by the underestimates of simulated water withdrawals. Indeed, we used 2007-2009 LPIS data to determine whether land parcels could be irrigated, which might have biased estimates of irrigation status before and after this period. In this perspective, it would be reasonable to update these data using specific sources, such as recent multi-sensor, high-resolution time series of satellite images being evaluated for identifying irrigated crops in our study region (Waldner et al. 2015b).

Second, the allocation of irrigation equipment to irrigated land parcels should be improved by collecting information about relative frequencies and distributions of types of irrigation equipment. The type of irrigation equipment strongly influences irrigation volume per ha. Discussions with irrigation experts indicate that the increasing use of pivot irrigation tends to increase irrigation intensity. Methods to obtain irrigation equipment information should be developed.

Third, our crop classification was developed to discriminate crops based on their irrigation use, but it may be oversimplified. We ignored irrigated crops that covered small areas. For example, we gathered in a unique “seed production” class the main seed crop (maize) and many other seed crops found in the Tarn area (e.g. carrots, onions).

Fourth, the estimation of crop management could certainly be improved. On the one hand, we simplified the description of rainfed crops because we primarily wanted to reproduce water withdrawals correctly. On the other hand, crop management of irrigated crops, although detailed, depended on the experience of key informants in local crop management practices.

Fifth, the collected data is dependent on the key informants. In our case, the selected key informants ranged from a highly experienced extension agent, who had worked in the same area for approximately 20 years, to a recently recruited agent. In general, the longer their experience in local farming, the greater their ability to describe crop management decision rules at the regional scale, though their answers appeared to be adapted to average pedo-climatic conditions. Conversely, the shorter their experience, the more they tended to refer to extension service bulletins, i.e. recommendations instead of actual practices. The key informants with less experience tended to provide detailed descriptions of farmers’ decision rules; however, the information was restricted to the most recent years. Ultimately, we had to find a balance between the reliable experience of the former and the high detail of the latter. In this regard, the intermediate objects used during the interviews (maps, tables and diagrams) allowed to frame the respondents answers, so as to enable their comparability and following encoding.

Genericity and replicability. Our approach of describing cropping systems at the regional scale was applied to the Tarn and Adour watersheds in response to specific irrigation issues. However, it has a generic character. First, it uses data that is relevant beyond these two study areas. The LPIS database, from which we obtained descriptions of crop sequences, is increasingly used to map crop patterns and dynamics in France (Durpoix and Barataud 2014; Rizzo et al. 2014; Bouty et al. 2015; Levavasseur et al. 2016) and elsewhere in Europe (Leteinturier et al. 2006; Levin 2013; Zimmermann et al. 2016). Second, the local information was integrated using intermediate objects (e.g., diagrams) and then formalized as IF-THEN rules for management decisions and cropping system location. Combining diagrams and IF-THEN rules defined a methodological framework that can be adapted easily to study other areas and crop management practices besides irrigation, as well as to account for various annual and perennial crops. We found that the intermediate objects prepared for the interviews (scripts and diagrams) could be adapted rapidly from the first area (Tarn) to the second (Adour), demonstrating their genericity. Formalizing the knowledge that underpins the intermediate objects used for key informant interviews may eventually facilitate social learning among farmers, extension agents and scientists, at least by providing focal points for communication and bridging gaps among them (Jakku and Thorburn 2010; Houllier and Merilhou-Goudard 2016; Moonen et al. 2016). More generally, we assume the key informant approach can be repeated anywhere, and also extended to the collection of other data, e.g. of crop rotations and several technical operations, where or when generic database are not available, as did Mignolet et al. (2004). Though, its main limitation, as in other participatory approaches, is the difficulty in identifying the best key informants. One way to evaluate their representativeness is by characterizing the local web of actors and the socio-technical system (Mathevet et al. 2014). We limited our key informant approach to extension agents, but other local actors have knowledge about crop management practices that complements farmers' knowledge. During the interviews, managers of local water-user associations, who are also farmers, or extension agents working for private or crop-specific technical institutes, were often mentioned as able to provide relevant knowledge to describe cropping systems and irrigation practices at the regional scale.

Evaluation. More complete evaluation of our approach would have been based on an independent dataset of observed farmers' practices. This dataset would have included all (or nearly all) farms within the region to address the high heterogeneity of farmers' strategies. A dataset corresponding to a sample cannot represent the entire population and is thus insufficient for complete evaluation. However, no exhaustive dataset was available. The lack of adequate data is a major obstacle in evaluating model outputs, as often reported for model evaluation at the regional scale (e.g. Leenhardt et al. 2016; Temme and Verburg 2011; Waldner et al. 2015a). Due to the lack of independent data on observed farmers' practices, we could not evaluate our approach directly; thus, we used a simulation model to assess its ability to provide consistent estimates of water withdrawals. We used AEAG water withdrawal data as a validation dataset despite its weakness in spatial coverage, locations of withdrawal points and how withdrawn volumes were surveyed over time. The differences between observed and simulated water withdrawals were due in part to these inaccurate observations, but also likely due to underestimates of irrigation of orchards and vegetables by the model, particularly in the Tarn area, because the soil-crop model in MAELIA was not sufficiently parameterized to represent these two crops correctly. Another option to evaluate our approach, despite the lack of observed cropping system data, could have been to involve farmers (or other local experts not previously involved) and verify whether the simulated dates for the main technical operations (sowing, harvest) were consistent with their field knowledge. This would have required summarizing the temporal distribution of the corresponding technical operations for each combination of [crop sequence type] × [soil] × [irrigation equipment] for each crop into diagrams similar to those used during the interviews (Fig. 2). These alternative ways to assess our approach, however, are mainly qualitative and rely on either the quality of farmers' expertise or the availability of new experts.

5. Conclusions

Describing cropping systems at the regional scale requires integrating generic data sources with formalized local expert knowledge. The major challenge concerns the data on crop management practices due to the high spatial and temporal heterogeneity of farmers' decision making. We evaluated the contribution of a key informant approach to simplify the survey and modeling of crop management practices. Comparison of our approach to that in a previous study (Murgue et al. 2016) indicated that we needed only one-fourth the time to collect and process the relevant information. Our simplified approach involved only 12 interviewees compared to the sample of 27 farmer interviews (and several focus groups) in the previous study. The gain in efficiency was even greater because our study areas were a total of six times as large as that in the previous study. Implementing the key informant approach allowed us to model irrigation decisions and their spatial distributions and, through dynamic simulations, to predict annual amounts and interannual dynamics of irrigation water withdrawals relatively well. One main innovation of our method was to use knowledge from generic databases when interacting with key informants and ad-hoc intermediate objects to help them focus on missing information. In particular, use of diagrams reduced interview duration and processing time. These intermediate objects are easy to reuse in new study areas. This approach was applied to two large areas and can easily be adapted to other areas where LPIS data are available. Although we focused on irrigation management practices in areas with water scarcity issues, this approach is sufficiently generic to be applied to areas, and can be easily adapted to focus on other management practices and crops. Thus, our approach can be considered a rapid and inexpensive tool to inform decisions and policy making to address agri-environmental issues that require modeling of the spatial distribution of cropping systems at the regional scale.

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