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A dynamic model for water management at the farm level integrating strategic, tactical and operational decisions

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A B S T R A C T

Farming systems are complex and have several dimensions that interact in a dynamic and continuous manner depending on farmers' management strategies. This complexity peaks in Indian semi-arid regions, where small farms encounter a highly competitive environment for markets and resources, especially unreliable access to water from rainfall and irrigation. NAMASTE, a dynamic computer model for water management at the farm level, was developed to reproduce interactions between decisions (investment and technical) and processes (resource management and biophysical) under scenarios of climate-change, socio-economic and water-management policies. The most relevant and novel aspects are i) system-based representation of farming systems, ii) description of dynamic processes via management flexibility and adaptation, iii) representation of farmers' decision-making processes at multiple temporal and spatial scales, iv) management of shared resources. NAMASTE's ability to simulate farmers' adaptive decision-making processes is illustrated by simulating a virtual Indian village composed of two virtual farms with access to groundwater.

1. Introduction

Agriculture faces many challenges regarding its productivity, revenue and environmental and health impacts, challenges that must be considered within the known context of climate change. Agriculture also faces demands to increase the quantity, quality, accessibility and availability of production to secure food production and improve product quality to address needs of the world's growing population (Meynard et al., 2012; Hertel, 2015; McKenzie and Williams, 2015). Agricultural productivity must increase within a framework of environmental and health concerns. To do so, agriculture should decrease its environmental impacts on water, air, soil and aquatic environments and consider the scarcity of resources such as water, phosphorus and fossil fuels (especially for production of nitrogen fertilizers) (FAO, 2011; Brown et al., 2015). Under climate change, warmer temperatures, changes in rainfall patterns and increased frequency of extreme weather are expected to occur. Consequently, it has direct, biophysical effects on agricultural production and can negatively affect crop yields and livestock (Nelson et al., 2014). Rising sea-level will increase risks of flooding of agricultural land in coastal regions, while changes in rainfall patterns could increase growth of weeds, pests and diseases (De Lapeyre de Bellaire et al., 2016).

On the Deccan Plateau in India, the countryside has witnessed the proliferation of individual, electrical pump-driven borewells that extract water from underground aquifers (Sekhar et al., 2006; Javeed et al., 2009). The low productivity of the aquifer (Dewandel et al., 2010; Perrin et al., 2011) and a rapid decline in the water table level has decreased borewell yields (Ruiz et al., 2015), indicating that (groundwater) irrigated agriculture still largely depends on rainfall. For a region that depends largely on monsoon and winter rainfall to maintain agricultural production, any shift in climate would have a severe impact on natural resources and the economy. Drilling borewells to gain control over water access

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is crucial to maintain household sustainability; however, it also entails the risk of failed borewells and intractable debts (Taylor, 2013).

Modeling and quantifying spatio-temporal variability in water resources and interactions among groundwater, agricultural practices and crop growth is an essential component of integrated and comprehensive water resource management (Ruiz et al., 2015). Simulating scenarios of climate change and water management policies is an essential tool to identify mechanisms that farmers can use and policies that can be implemented to address these challenges (White et al., 2015). In these modeling and simulation approaches, farmers' decision-making processes should be considered to assess how agricultural production systems change and adapt to external changes and opportunities. Farm management requires farmers to make a set of interconnected and successive decisions over time and at multiple spatial scales (Risbey et al., 1999; Le Gal et al., 2011). In the long term, farmers decide on possible investments and marketing strategies to select or adapt to best fulfill their objectives. Decisions about cropping systems also impact the farm. Decisions about crop rotation and allocation are considered at the whole-farm level (Detlefsen and Jensen, 2007; Castellazzi et al., 2008; Dury et al., 2010) and can be investigated in the long term and/or adapted for shorter periods. Once a crop is chosen, farmers must make (intra-) annual decisions to choose crop management techniques and the varieties to sow in the coming year. This decision can be made before cultivation and adapted, if necessary (tactical decisions). Generally, this decision concerns the whole farm to ensure that practices are consistent or to maintain a minimum of crop diversity on the farm. However, tactical decision descriptions are not sufficient to trigger daily operational management. Therefore farmers must define specific ways to execute their tactical plans. Farmers decide on crop operations and resource management and even change the purpose of their crops when conditions are not conducive to the initial plan. A farm decision-making model should include sequential aspects of the decision-making process and farmers' abilities to adapt and react (Akplogan, 2013). According to a review of modeling adaptive processes in farmers' decision-making (Robert et al., 2016a), 70% of the articles reviewed focused on only one stage of the decision: adaptation at the strategic level for the entire farm or at the tactical level for the farm or plot. We suggest reconsidering farm management as a decision-making process in which decisions and adaptations are made continuously and sequentially over time (the 3D approach: strategic Decisions/tactical Decisions/operational Decisions) to simulate reality more closely.

These considerations prompted the development of a simulation model able to reproduce interactions between decisions (investment and technical) and processes (resource management and biophysical) under scenarios of climate-change, socio-economic and water-management policies. This article presents this farming system model and an example of its application to a semi-arid region in Karnataka state, southwestern India. We first introduce the conceptual model and the modeling and simulation platform. We then describe the model – NAMASTE – in detail and illustrate its capabilities by applying it to a case study in southern India. Finally, we discuss the key modeling choices and present several insights on how to upscale the model from the farm level to watershed, regional and national levels.

2. Materials and methods

2.1. Conceptual modeling

We divided the systemic representation of the farming system into three interactive systems: i) decision system, which describes farmers' continuous and sequential decision process; ii) operating system (technical system), which translates decisions ordered by the decision system into instructions to execute tasks which is an action to perform on a biophysical object or location (e.g. sowing operation); and iii) biophysical system, which describes crop and soil dynamics and their interactions, especially relations between groundwater, soil, and plant development, using a crop model (Clouaire and Rellier, 2009; Le Gal et al., 2010; Dury, 2011; Akplogan, 2013; Robert et al., 2016b) (Fig. 1).

For the decision model, we consider farmers as cognitive agents able to think, memorize, analyze, predict, and learn to manage future events and plan their actions (Le Bars et al., 2005). In artificial intelligence and cognitive sciences, agents are commonly represented as Belief-Desire-Intention (BDI) agents (Bratman, 1987; Rao and Georgeff, 1991). The BDI framework is founded on the well-known theory of rational action in humans. BDI agents are considered to have an incomplete view of their environment (Simon, 1950; Cyert and March 1963). The concept of Belief represents a farmer's knowledge of the farming system and its environment. Desires are a farmer's objectives (goals that meet production or management goals). Intentions are action plans that achieve a farmer's objectives (Desires).

Farmers are represented as BDI agents at several levels of the conceptual model of the farming system. Farmers' beliefs and desires are the basis of the production processes in the farming systems. Farmers manage their farms based on their knowledge and objectives. Farmers have different types of knowledge about their farms: structural (i.e. farming structure and organization), procedural (i.e. know-how of farming practices), and observable (i.e. observations about their environment). Observing social and economic environments is important to be able to quickly respond to changes and uncertainties in the production context. The climate, prices of crops and inputs, and availability of external resources such as groundwater, labor or shared equipment are common uncontrollable data farmers use to make decisions. They also adapt their practices based on recent outputs of production systems, such as yields. Decision models provide the plans that farmers will execute in their production systems based on their observations and objectives, which translates into actions (invest, perform a crop operation, etc.) that correspond to intentions of the BDI agent. Contrary to these actions, which are direct outputs from the farmer decision-making model, other outputs are consequences of these actions on the biophysical system, such as impact on groundwater: water consumption due to the volume of water pumped and drainage due to the natural return of excess water from rainfall and irrigation (for more details, see Robert et al. (2016b)).

2.2. RECORD: a modeling and simulation computer platform

2.2.1. Overview

The RECORD platform is a modeling and simulation computer platform devoted to the study of agro-ecosystems (Bergez et al., 2013). RECORD facilitates design of simple single (atomic) or hierarchical complex (coupled) models and enables using different temporal and spatial scales within models. It is based on the Virtual Laboratory Environment (VLE), a free and open-source multi-modeling and simulation platform based on the Discrete Event System Specification (DEVS) formalism that derives from the theory defined by Zeigler et al. (2000) on modeling and simulation for dynamic systems with discrete events. VLE provides a simulation engine, modeling tools, software libraries, and an integrated development environment to the RECORD platform. Specific extensions have been developed in RECORD to bridge the gap