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Université Toulouse 3 Paul Sabatier (UT3 Paul Sabatier)

Présentée et soutenue par :
Mme MARION ROBERT

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Directeur(s) de Thèse :

M. JACQUES-ERIC BERGEZ (INRA TOULOUSE)
M. ALBAN THOMAS (INRA TOULOUSE)

Jury :

M. THIERRY LAMAZE, CESBIO UPS, Président
Mme FLORENCE JACQUET, INRA MONTPELLIER, Rapporteur/Membre
M. KEN GILLER, WAGENINGEN UNIVERSITY, Rapporteur
M. BENOIT DEDIEU, INRA THEIX, Membre
Mme FRANCOICE CARPY-GOULARD, AEAG, Membre

Modeling adaptive decision-making of farmer: An integrated economic and management model, with an application to smallholders in India

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Modélisation des décisions adaptatives de l'agriculteur : Un modèle économique et décisionnel intégré, avec un cas d'étude en Inde

Marion Robert

PhD Manuscript

ABSTRACT

This thesis develops and discusses farmers' decision-making modeling approaches for representing the adaptation of farming to global changes and water policies: their effects on agricultural economics and practices and water resources comprise critical information for decision makers. After a summary, six articles are presented.

The first article reviews bio-economic and bio-decision models, in which strategic and tactical decisions are included in dynamic adaptive and expectation-based processes, in 40 literature articles.

The second article describes the case-study and presents a typology of Indian farmers from a survey including 684 farms in Berambadi, an agricultural watershed in South India.

The third article presents a step-by-step approach that combines decision-making analysis with a modeling approach inspired by cognitive sciences and software-development methods. This methodology bridges the gap between field observations and the design of the decision model. It is a useful tool to guide modelers in building decision model in farming system.

The fourth article describes the conceptual model NAMASTE, which was conceived to represents farmers adaptation processes under uncertainty. Since NAMASTE was designed in an extreme case of highly vulnerable agriculture, its generic framework and formalisms can be used to conceptually represent many other farm production systems.

The fifth article investigates the role of water management policies on groundwater resource depletion under climate change conditions. We built a stochastic dynamic programming farm model. The model reproduced decision on irrigation investment and cropping system made each year with the concern of future impacts on water availability for irrigation.

The sixth article describes the NAMASTE dynamic simulation model developed to model farming systems for evaluation and test of water management policies.

Key-words: farmers' decision-making, farm typology, conceptual model, stochastic programming, water management policies, climate change, Berambadi watershed.

RESUME EN FRANÇAIS

Cette thèse développe et discute une approche de modélisation des processus de décision des agriculteurs qui prend en compte l'adaptation des pratiques aux changements globaux et aux politiques de l'eau. En effet ces changements ont des effets sur l'économie et les pratiques agricoles ainsi que sur les ressources en eau et sont des informations essentielles pour la prise de décision. Après un synoptique de thèse, six articles sont présentés.

Le premier article est une revue de littérature d'une quarantaine d'articles sur les modèles bio-économiques et bio-décisionnels, dans laquelle les processus d'adaptation sont inclus dans les décisions stratégiques et tactiques.

Le deuxième article décrit le cas d'étude et présente une typologie des agriculteurs indiens déterminée à partir de 684 enquêtes d'exploitations agricoles dans le bassin versant agricole du Berambadi, au sud-ouest de l'Inde.

Le troisième article présente une méthodologie qui combine l'analyse des processus de décision avec une approche de modélisation inspirée des sciences cognitives et des méthodes de développement informatique. Cette méthodologie permet le passage entre les observations de terrain et la conception du modèle de décision. Il s'agit d'un outil utile pour les modélisateurs qui les guide dans la construction de modèles de décision pour les systèmes agricoles.

Le quatrième article décrit le modèle conceptuel NAMASTE, conçu pour représenter les processus adaptatifs de décision des agriculteurs dans un environnement incertain. Puisque NAMASTE a été conçu dans un cas extrême d'agriculture très vulnérable, son cadre et ses formalismes génériques peuvent être utilisés pour représenter conceptuellement de nombreux autres systèmes de production agricole.

Le cinquième article étudie le rôle des politiques de gestion de l'eau sur la baisse des ressources en eau souterraine dans des conditions de changement climatique. Nous avons construit un modèle agricole de programmation dynamique stochastique. Le modèle reproduit les décisions annuelles d'investissement en irrigation et de choix de systèmes de cultures réalisées avec le souci des impacts futurs sur la disponibilité de l'eau pour l'irrigation.

Le sixième article décrit le modèle dynamique de simulation NAMASTE développé pour l'évaluation et le test de politiques de l'eau sur les processus de décision des agriculteurs et la nappe phréatique.

Mots-clés: processus de décision des agriculteurs ; typologie des exploitations agricoles ; modèle conceptuel ; programmation stochastique dynamique ; politiques de gestion de l'eau ; changement climatique ; bassin versant du Berambadi.

PREFACE

I chose to present my thesis in an original way. As my written restitution is based on six articles either submitted or close to be submitted, and as it could be quite tedious to read and reread the article introductions that globally deal with the same theme (the one of my thesis), I chose to make a synoptic document of the thesis. This document of forty pages, gives in one hand the major advances (key messages found in the articles), and in the other hand deals with the introduction, the research approach and discussion-perspectives on the work that I conducted in depth. The reader can thus have an overview of the work done and go, if necessary, read the different articles. I also chose to provide a number of appendixes which could not be added to the articles but which can help understanding methodological items that could also be used by other researchers.

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LIST OF PUBLICATIONS

Published or submitted to peer-reviewed journals

[1]*Robert, M, Hu, W., Nielsen, M.K., Stowe, C.J. (2015) Attitudes towards implementation of surveillance-based parasite control on Kentucky Thoroughbred farm – current strategies, awareness and willingness-to-pay, *Equine Veterinary Journal*, Vol. 47 (6), doi: 10.1111/evj.12344

[1]*Robert, M., Stowe, C.J. (2016) Ready to Run: Price determinants of Thoroughbred from two-year-olds in training sales, *Applied Economics incorporating Applied Financial Economics*, Vol. 48, doi: 10.1080/00036846.2016.1164817

Robert, M., Dury, J., Thomas, A., Therond, O., Sekhar, M., Badiger, S., Ruiz, L., Bergez, J.E. (2016) CMFDM a methodology to guide the design of a conceptual model of farmers' decision-making processes, *Agricultural Systems*, Vol. 148, p 86-94, doi: 10.1016/j.agsy.2016.07.010

Robert, M., Thomas, A., Sekhar, M., Badiger, S., Ruiz, L., Raynal, H., & Bergez, J. E. (2016). Adaptive and dynamic decision-making processes: A conceptual model of production systems on Indian farms. *Agricultural Systems,* doi : 10.1016/j.agsy.2016.08.001

Robert, M., Thomas, A., Bergez, J.E. (2016) Integrating adaptative processes in farming decision-making models – a review, *Agronomy for Sustainable Development*, doi: 10.1007/s13593-016-0402-x

Robert, M., Thomas, A., Sekhar, M., Badiger, S., Ruiz, L., Willaume, M., Leenhardt, D., Bergez, J.E. (2016) Typology of farming systems for modeling water management issues in the semi-arid tropics (Berambadi watershed, India), *Water* (under review)

Robert, M., Bergez, J.E., Thomas A (2016) Stochastic dynamic programming approach to analyze adaptation to climate change - application to groundwater irrigation in India, *European Journal of Operational Research* (submitted)

Robert, M., Thomas, A., Sekhar, M., Raynal, H., Casellas, E., Casel, P., Chabier, P., Joannon, A. & Bergez, J. E (2016) NAMASTE: a dynamic model for water management at the farm level integrating strategic, tactical and operational decisions, Environmental Modelling & Software (submitted)

[1] * Corresponds to publications that are not connected to the work presented in this thesis.

Abstracts and proceedings

Robert, M., Thomas, A., Bergez, J.E. (2015) Modeling Adaptive Decision-Making of Farmer: an Integrated Economic and Management Model, with an Application to Smallholders in India In: the 5th International Symposium for farming Systems Design (FSD) ‘Multi-functional Farming systems in a changing world, 5th-10th September 2015, Montpellier, France

Robert, M., Thomas, A., Bergez, J.E. (2016) CMFDM: A methodology to guide the design of a conceptual model of farmers’ decision-making processes. In: the 8th International Congress on Environmental Modeling and Software Society (iEMSs), 12th-14th July 2016, Toulouse, France

Robert, M., Thomas, A., Bergez, J.E. (2016) NAMASTE: A dynamic integrated model for simulating farm practices under groundwater scarcity in semi-arid region of India In: the 14th Congress on European Society of Agronomy (ESA), 5th-9th September 2016, Edinburgh, Scotland

Additional scientific contributions

Member of the scientific committee of the *Ecole Chercheurs* « Approches interdisciplinaires de la modélisation des agroécosystèmes » that will be hold the 7th-10th March 2017.

CONTENTS

LIST OF ACRONYMS

ACCAF: Adaptation to Climate Change of Agriculture and Forest

AICHA: Adaptation of Irrigated Agriculture to Climate Change

AMBHAS: Assimilation of Multi-satellite data at Berambadi watershed for Hydrology And land Surface experiment

BDI: Belief-Desire-Intention

CEFIPRA: Centre for the Promotion of Advanced Research

CETIOM: Centre Technique Interprofessionnel des Oléagineux Métropolitains

CMFDM: Conceptual Modeling of the Farmer agent underlying Decision-Making processes

CRASH: Crop Rotation and Allocation Simulator using Heuristics

CTA: Cognitive-Task Analysis

DP: Dynamic programming

DSP: discrete stochastic programming

EDT: Doctoral School of the University of Toulouse

INRA: French National Institute of Agronomy

NAMASTE: Numerical Assessments with Models of Agricultural Systems integrating Techniques and Economics

NDM: Naturalistic decision making

RECORD: Renovation and COORDination of agro-ecosystem modeling

STICS: Simulateur multidisciplinaire pour les cultures standard

UML: Unified Modelling Language

Chapter 1

Introduction – Synthesis Chapter

1.1. General introduction

1.1.1. Today's and tomorrow's challenges for the agriculture

Agriculture is facing many challenges both in terms of productivity and revenue and in terms of environmental and health impacts. Agriculture must thus face a demand for increasing production regarding quantity, quality, accessibility and availability to secure food production and improve product quality to cope the needs of the world's growing population (Meynard et al. 2012; Hertel 2015; McKenzie and Williams 2015). The FAO (Food and Agriculture Organization of the United Nations) estimates that global agricultural production must increase by nearly 60% from 2005/2007 to 2050 to meet the food demand of the estimated 9 billion people by 2050 while ensuring fair incomes for farmers (FAO 2012). Increasing agricultural productivity is all the more important to face the increasing competition for land, water and investment between urban, agricultural and industrial sectors (FAO 2011).

However, increasing agricultural productivity must be made within a framework of environmental and health constraints. First it should consider limiting the impact on the environment, by reducing the impacts on water and aquatic environments (nitrate, pesticide, drug residue pollutions through leaching and runoff), on air (nitrous oxide, methane, ammonia and other greenhouse gas) and finally on soil (soil structural discontinuity, compacted areas, risk of leaching and erosion, decline in soil biodiversity). It should also consider limiting habitat modification to encourage and maintain biodiversity. Second, agricultural productivity should take into account the scarcity of resources mobilized by agricultural production such as water resources, phosphorus and fossil energy (particularly for the production of nitrogen fertilization) (FAO 2011; Brown et al. 2015).

These agricultural challenges also have to be considered within the known context of climate change. Under climate change conditions, warmer temperatures, changes of rainfall patterns and increased frequency of extreme weather are expected to occur. The global mean temperature expected by the end of this century could be 1.8° to 4.0°C warmer than at the end of the previous century within an uneven pattern across the globe. Climate change could lead to extreme climatic events, such as increased intensity and frequency of hot and cold days, storms, cyclones, droughts and flooding (Anwar et al. 2013). Climate change alters weather conditions and thus has direct, biophysical effects on agricultural production and would negatively affects crop yields and livestock (Nelson et al. 2014). Sea-level rises will increase the risk of flooding of agricultural land in coastal regions. Changes in rainfall patterns may support the growth of weeds, pests and diseases (Lapeyre de Bellaire and al. 2016).

1.1.2. Designing farming systems

Facing the aforementioned challenges, conventional farming systems have their limitations and a particular attention is made on the dynamics of innovations likely to consider and resolve the former issues (Novak 2008). In a broad sense, innovation is seen as the action of "transforming a discovery on a technique, a product or a conception of social relationship into new practices" (Alter 2000).

In agronomy, innovation is generally defined as a process which promotes the introduction of new changes and leading to its spread and its recognition through applications cases (INRA Sens 2008; Klerkx et al. 2010). Innovation requires a design process based on scientific and / or empirical knowledge. The design process is conducted by agricultural and development research institutes in close collaboration with farmers to address their needs, their constraints and their knowledge on agricultural production systems (Le Gal et al. 2011).

Two ways of designing systems are distinguished: i) the rule-based design aims at gradually improving existing technologies and systems, based on predefined objectives and standardized evaluation processes (Meynard et al. 2012); ii) the innovative design is built to meet completely new expectations initially undetermined but getting more and more specific as the exploration process takes shape (Meynard et al. 2012; Lefèvre et al. 2014). In an uncertain and changing environment, traditional rule-based analytical frameworks are challenged. The adaptable design approaches that take into account varying objectives, skills and modes of validation and do not need to be specified in advance may be preferable (Meynard et al. 2012).

Different tools and methods have already been developed to address the issue of farming system designs. Loyce and Wery (2006) classified them into three groups: (i) diagnosis (e.g. Doré et al. 1997) allows to understand and evaluate agricultural systems from field measurements and surveys, (ii) prototyping (e.g. Vereijken 1997) consists in designing a limited number of systems based on expert-knowledge, in testing and evaluating them, and in adapting the prototypes; (iii) model and simulation based approaches (e.g. Romera et al. 2004) where the model allows to design a simplified representation of a real system and the simulation allows to change the state of the system in order to understand and evaluate its behavior.

Given the complexity of the agricultural production systems, simulation modeling is a commonly used tool for the design and the evaluation of innovative agricultural production systems (Bergez et al. 2010). Indeed, systemic modeling and dynamic simulations appear to be powerful tools to represent the dynamic interactions between biological and technical processes at different time and space scales and to assess and quantify the performances of a variety of alternative systems for a diversity of production contexts (Bergez et al. 2013).

1.1.3. Agricultural production systems and complex systems

Definition and organization of farming systems

An agricultural production system is defined as a complex system of resources, technical activities, biological processes and decisional processes that aims at meeting farm production objectives by producing agricultural goods (Tristan et al. 2011). The agricultural production system is a complex matrix of interdependent items that are partially controlled by the farm manager or the farm household subjected to a socio-economic and climatic external environment (Figure 1.1).

Dury et al. (2013) identified five categories of objectives that drive decisional processes within farming systems: 1) financial like maintain, secure, increase or maximize farm income, 2) workload by decreasing, minimizing, maintaining or spreading working hours, 3) farm status considering the future of the farm, 4) technical aspects on crop management techniques, 5) environmental aspects with reasoning on biodiversity and pollution.

Decisional processes aim at developing a resource management strategy that transforms land, capital, labor resources into agricultural products taking into consideration infrastructure and intuitional constraints such as equipment, storage and transportation, marketing facilities and farm credits. This transformation is the result of farmer's short-term technical activities on the farm. The farmer mobilizes knowledge to make decisions based on know-how, skills and specific observations made previously on his production system.

Agricultural production system may be composed of several production sub-systems with specific production objectives. Three main production subsystems are identified in Coléno et al., (2005): crop production, animal production and transformation unit. These sub-systems are interrelated since the end product and wastes of one sub-system may be used as inputs in others (Figure 1.1).

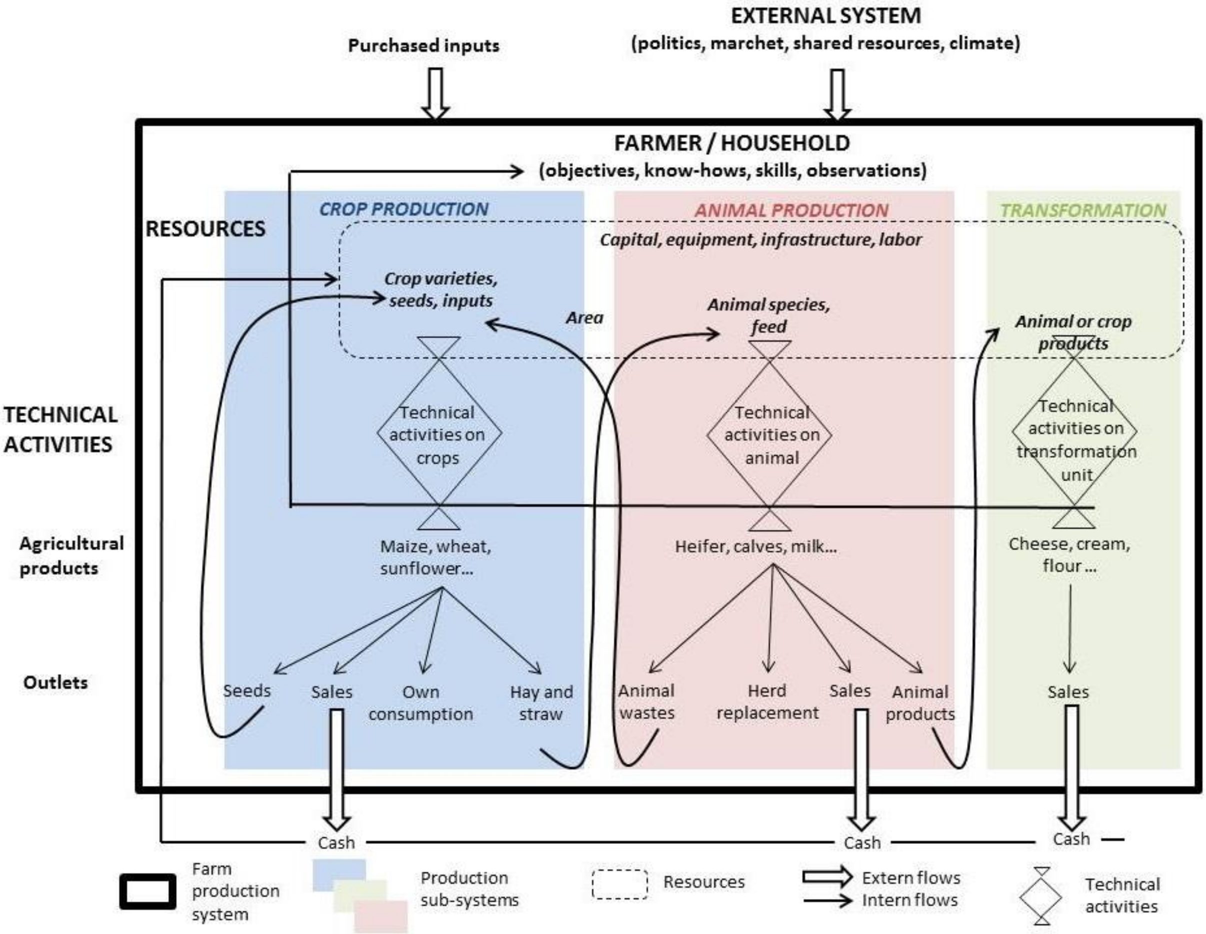

Figure 1.1 : Agricultural production system organized into three integrated production subsystems (from Coléno et al. 2005).

Management of farming system

The farmer dynamically plans and coordinates his technical activities on his farm at different time and space scales. However agricultural production systems are facing new challenges due to a constantly changing global environment that is a source of risk and uncertainty, and in which past experience is not sufficient to gauge the odds of a future negative event. Concerning risk, farmers are exposed to production risk mostly due to climate and pest conditions, to market risk that impact input and output prices, and institutional risk through agricultural, environmental and sanitary regulations (Hardaker 2004). Farmers may also face uncertainty due to rare events affecting, e.g. labor, production capital stock, and extreme climatic conditions, which add difficulties to the production of agricultural goods and calls for re-evaluating current production practices. To remain competitive, farmers have no choice but to adapt and adjust their daily management practices (Hémidy et al. 1996; Hardaker 2004; Darnhofer et al. 2010; Dury 2011).

Based on his past experience and on forecasts on weather and market prices, the famer can anticipate some events and production conditions. Thus he is able to plan several management options to face these different production conditions. However, given the limitations of human cognition to anticipate the future, everything cannot be anticipated (Chavas 2012). The farmer must therefore be able to establish a reflexive analysis on the observations he made on his environment in order to instantly review his initial management plan and if necessary his production objectives. The farmer's decision-making process is therefore a dynamic sequence of planning, observation, reflection, adaptation, implementation as technical activities and learning processes (Risbey et al. 1999; Le Gal et al. 2011). This variable and uncertain production context justifies why a management plan repeated over several years won't give the same production results and why different management plans may lead to the same production results. Farmer's decision-making is a continuous process in time and space. Farmers make decisions based on his visibility and expectations on the production context that impact his management on the long-, medium- or short-term. Decisions may affect the whole agricultural production system, a production sub-system or even smaller spatial unit such as the plot (Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010). For instance, investing in equipments, in buildings or in lands are decisions that reflect a willingness to expand or modernize the farm. These decisions have long-term consequences because 1) loans are often over several years, 2) the farm structure and infrastructures are changed for the coming years (life duration of a tractor, building, etc.). However, decisions on selecting varieties and crop management techniques have an impact on the short term and at a local scale corresponding to the production season and the plot. Finally, deciding to delay the sowing, to extend the water turns or to apply pesticide treatment will have an immediate effect on the biophysical system because these decisions correspond to technical activities executed on each plot.

Specificities of irrigated farming systems

A production system is considered as irrigated when water supply other than rainfall is provided on one or several plots. The irrigation water is pumped from a water point and distributed to the fields through appropriate water transport infrastructure. In irrigated production systems, crops benefit from both the contribution of rainfall and irrigation water to cover their water needs. Irrigation is an effective management tool against the variability and uncertainty of rainfall events. The irrigation water can come from surface water fed by the rainfall runoff like streams, rivers, ponds, lakes and dams. Irrigation water can also come from the aquifer that is fed by the rainfall drained into the ground. The deep aquifers are located between two impermeable layers leading to slow recharge compared to surface water reservoirs.

Irrigation water can come from different sources considered as collective when multiple users are identified or individual. Except for individual rainfall reservoirs, the other sources of irrigation are often subject to conflicts and management issues (Gleick 1993; Wolf 2007). Conflicts over rivers between upstream and downstream users are commonly seen as the upstream pumping will impact the downstream flow (Chokkakula 2015). On a reservoir, tensions appear when pumping exceeds the rainfall recharge from run-off particularly in drought conditions (Rajasekaram and Nandalal 2005).

For groundwater, pumping may exceed rainfall recharge. Moreover, lateral flows conduct the water table level to rebalance so that intensive pumping by one farmer impacts the yield of the neighbor's borewell (Janakarajan 1999).

1.1.4. Global challenges in designing agricultural production systems

The production of knowledge on agricultural production system is an important issue while designing such system. Several types of knowledge have to be produced to understand the complexity of systems: 1) knowledge on the system structure to understand its organization and composition; 2) knowledge on internal processes e.g. decision processes, biophysical processes; and 3) knowledge on inputs and outputs to understand the exchanges of information and matters within the system and with the external environment as well as the impact of an entity on another entity (how climate change impacts on farmers' decision making processes). The use of appropriate tools to collect and organize knowledge is important to ensure the quality of the knowledge production process.

Another challenge in designing agricultural production systems is to properly define the limits of the system to be designed. Agricultural production systems are too complex to be entirely designed as they are. The level of specificities and details to be considered depend on the initial research question.

Designing agricultural production systems requires considering the time and space scales at which processes should be represented. Some processes may occur at several time and space scales (e.g. decision processes), others are specific to only one scale (e.g. sowing is made a defined date on a defined plot). An interesting issue in designing systems is to be able to upscale or downscale a representation.

1.2. THESIS PROJECT

1.2.1. Research context

The Indian agriculture

India is the most populous country in the world after China. India has 17.5% of the global population with 1.26 billion people in 2015. The growth rate of its population was 1.2% in 2014. A third of the Indian population (212 million) is undernourished and lives below the extreme poverty line (Central Intelligence Agency 2016). Famine and poverty remain a major obstacle to the country development.

India is the world's fourth-ranking agricultural power. In 2014, Indian agriculture accounted for 17.8% of GDP and employed 49.7% of the workforce. India has an important agricultural area of over 190 million hectares of which 37% is irrigated. Climatic gradient, topographic and soil diversity allow a wide range of crops (India Brand Equity Foundation 2016). The main agricultural products are wheat, millet, rice, corn, sugarcane, tea, potato, cotton. Productivity and yields have risen sharply since the 1950s after the Green Revolution with the development of irrigation, the use of high-yield seeds and fertilizers and the availability of bank loans. However, subsistence farming is still dominant in India today. Farm households grow on small plots and crops are partly self-consumed (Dorin and Landy 2002). Indian farms have an average size of 1.5 hectares. This fragmentation of holdings is inheritance of the land reform made in 1947 after the Independence from the British that had the aim to redistribute land to poor farmers by restricting the size of the landed property (Chandra 2000). This fragmentation contributes to the low mechanization of farming where animal traction and manual labor are still dominant in Indian agriculture.

Three seasons regulate the farm cropping system: i) kharif (June to September) which corresponds to the South-West monsoon season, when almost all the cropping area is cultivated, either exclusively rainfed or with complementary irrigation; ii) rabi (October to January), the North-East monsoon season or winter season, when most of the plots where irrigation is possible are cultivated; and iii) Summer (February to May), the hot and dry season, when only few irrigated plots are cultivated. Despite the development of irrigation promoted by the Green Revolution, two-thirds of Indian agricultural production are still heavily dependent on the monsoon and are produced in kharif. Investments in infrastructure are also limited. Storage and conservation facilities of agricultural products are lacking in the rural area of the country and cause huge losses of up to 40% of crops for fruits and vegetables (Dorin and Landy 2002). After harvest, farmers are compelled to sell immediately their products and often at low prices. The lack of maintenance of irrigation canals and wells are causing the loss of over a third of transported water (Aubriot 2013). In this context of increasing population and industrial development, conflicts over the water resource use are increasing (Chokkakula 2015).

The Green Revolution also led to the main problems that the agricultural sector is facing today. The intensification of agricultural production with the massive use of fertilizers and pesticides heavily distorted the soil and led to a soil depletion with significant loss of nutrients (Dorin and Landy 2002). The intensive drilling and the development of submersible pumps caused a significant drop in the natural groundwater resources (Aubriot 2013). Climate change and rising temperatures are also encouraging intensifying irrigation. This intensification of practices and input uses increased the production cost of farmers who had to heavily borrow money. In addition, farmers still greatly rely on local merchants and wholesalers who push them to sell at low prices. Therefore, farmers are subject to multiple pressures that led some to desperate situations and even suicide. In recent years, the farmers' suicide rate has terribly increased (Mishra 2007). In 2014, the number of suicides has been estimated at 12 360, taking into account the population of farm owners and farm workers (National Crime Reports Bureau 2015).

The AICHA project

In the context of climate change and of agriculture increasingly relying on groundwater irrigation, it is crucial to develop reliable methods for sustainability assessment of current and alternative agricultural systems. The multi-disciplinary Indo-French research project AICHA (Adaptation of Irrigated Agriculture to Climate Change) (2013-2017) has aimed to develop an integrated model (in agronomy, hydrogeology and economics) to simulate interactions between agriculture, hydrology and economics and to evaluate scenarios of the evolution of climate, agricultural systems and water management policies.

The AICHA project is supported by the Indo-French Centre for the Promotion of Advanced Research (CEFIPRA), and the INRA flagship program on Adaptation to Climate Change of Agriculture and Forest (ACCAF),and includes researchers from the Indian Institute of Sciences (IISc), the Indo-French Cell on Water Science (IFCWS), Ashoka Trust for Research in Ecology and the Environment (ATREE), the French National Center of Scientific Research (CNRS) (UMR COSTEL) and the French National Institute for Agricultural Research (INRA) (UMR SAS, UMR LERNA, UMR AGIR, UMR EMMAH, UR RECORD).

The Berambadi watershed situated in the south west of India, with an area of 84 km², is an ideal site for this project. The Berambadi watershed is small enough to allow fine monitoring and large enough to include a large part of the variability of agricultural systems. It has been developed as a research observatory since 2002 by the Indo-French Cell of the Water Science Cell (LMI IFCWS − IISc/IRD) in Bangalore. It belongs to the Kabini river basin (about 7000 km², southwest of Karnataka), which is a tributary of the Kaveri River basin.

Due to the rain shadow of the Western Ghats on the South West monsoon rains, the Kabini basin exhibits a steep rainfall gradient, from the humid zone in the west with more than 5000 mm of rain per year to the semi-arid zone in the East with less than 700 mm of rain per year. The Berambadi watershed being in towards the East of the Kabini, its climate is tropical sub-humid (aridity index P/PET of 0.7) with a rainfall of 800 mm/year and PET of 1100 mm on average (Sekhar et al. 2016). A moderate East-West rainfall gradient is observed at the scale of the watershed, with around 900mm rainfall per year upstream (West) and less than 700mm rainfall per year downstream (East).

For the past 50 years the climate variability has intensified in this region (Jogesh & Dubash 2014). Predictions for 2030 announced an increase in temperature of 1.8 to 2.2 ° C, associated with lower annual rainfall especially during the monsoon (Jogesh & Dubash 2014). For a region such as southern India whose farm production heavily depends on monsoon and winter months, climate change will have severe repercussions on natural resources and on the agricultural economy.

Black soil (Vertisols and Vertic intergrades), red soil (Ferrasols and Chromic Lusivols) and rocky/weathered soil are the main soil types in the area and are representative soil types for granitic/gnessic lithology found in South India. These are representative of the soil types for granitic/gnessic lithology found in South India (Barbiéro et al. 2007). The hard rock aquifer is composed of fissured granite underlain by a 5-20 m layer of weathered material. Groundwater transmissivity and borewell yields decrease with water table depth (Maréchal et al. 2010).

During centuries, the traditional system of "tanks" has been efficiently used to extend the cropping season with the water stored during monsoon (Dorin and Landy 2002). However, poor maintenance of the water tanks and increasing silt deposition decreased its efficiency over time. At the Indian independence from the British in 1947, Prime Minister Jawaharlal Nehru decided that developing agriculture would be the priority of the country. He promoted huge irrigation projects based on the construction of large dams. This fundamentally altered the demand for irrigation in the Cauvery watershed and shifted the focus from not only using water flowing into the sea but also to dividing water resources (Pani 2009). The significance of this technological change was intensified by the growing demand for water. In the rural economy, the Green Revolution strategy that started in the 1960s was based on high yield seeds, chemical fertilizers and irrigated agriculture, which meant increasing the demand for water. The development of submersible pump technology in the 1990s resulted in a dramatic increase in borewell irrigation (Sekhar et al. 2006; Javeed et al. 2009). However, the fissured structure of the hard rock aquifer lowers the success ratz of drilled borewells. Indeed, whatever the borewell depth, it has to cross a fissure to get water in (Figure 1.2).

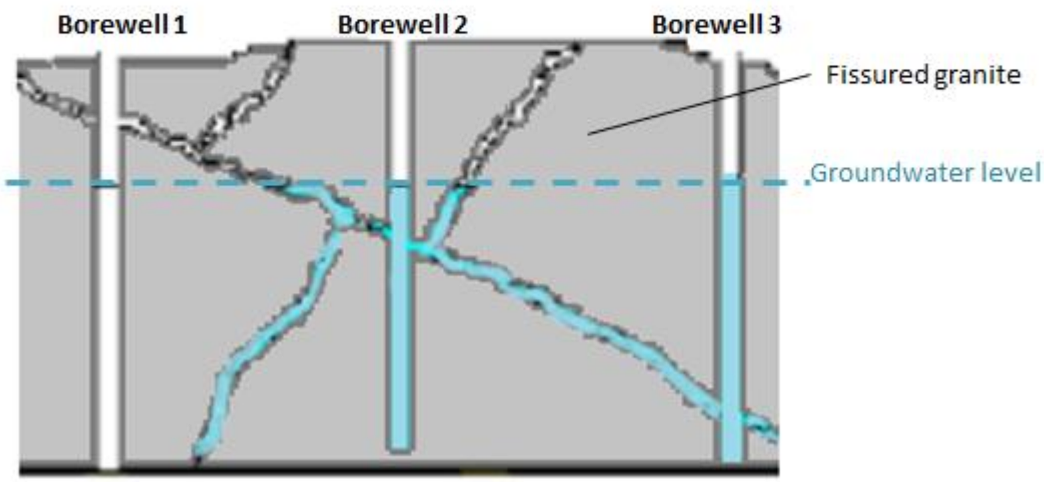

Figure 1.2 : Hard rock aquifer composed of fissured granite underlain by a 5-20 m layer of weathered material: only two borewells have access to groundwater (from Jacoby, 2015).

This shift from collective tanks to individual borewells has been largely encouraged by public policies that provide free electricity to farmer for groundwater irrigation. Thus, it led to considerable dependency from agriculture practices on irrigation groundwater. Increasing pumping combined with the low productivity of the aquifer lead to a rapid decline in the water table level (Dewandel et al.

2010; Perrin et al. 2011) and a decrease of borewell yields (Ruiz et al. 2015). As a consequence, continuous pumping leads to groundwater table drawback and reduces the availability of groundwater for irrigation (Dewandel et al. 2010; Perrin et al. 2011). This feedback makes predefined land-use scenarios unrealistic, since farmers need to adapt their actions continually according to groundwater availability (Ruiz et al. 2015).

The main originality of the project lies on its multidisciplinary approach that combines on the one hand the economic impacts on agricultural production and on the hydrological regime and on the other hand the feedback effects of the hydro-climatic-economic impact on farming practices, on land use and on agricultural productivity. The project involves several scientific issues. It aims at developing an integrated eco-agro-hydrological model able to take into account the direct effects of agricultural practices on water resources and the feedback effects by considering the adaptive behavior of farmer to climate change, resource availability and market development. This integrated modeling approach also answers the question of optimal water resource management in a context of increasing scarcity. It also deals with the issue of distribution of water resources and agricultural land in the context of climate change. The AICHA project analyzes scientific questions such as:

• modeling the hydrological transfers and their relationship with agricultural practices

• coupling of economic models with agronomic simulators

• testing alternative scenarios of water resource management policies at the watershed scale.

1.2.2. Thesis objectives

Agricultural production systems are facing new challenges due to an ever changing global environment that is a source of risk and uncertainty. To adapt to these environmental changes, farmers must adjust their management strategies and remain competitive while also satisfying societal preferences for sustainable food systems. Representing and modeling farmers' decision-making processes by including adaptation is therefore an important challenge for the agricultural research community. Three issues are at the core of this research:

Represent farmers' decision-making and adaptation processes

- What are the engaged processes in farmers' decision-making?

Farmers' decision-making processes are a combination of decision stages: i) the strategic decision stage, with a long-term effect (years to decades) on whole-farm organization (e.g., decisions about equipment investment, infrastructure development or farm expansion); ii) the tactical decision stage, with a medium-term effect (several months or seasons) on the farm cropping system and its resource management; and iii) the operational decision stage, with a short-term effect restricted to specific plots and describing daily adjustments to crop management practices (Risbey et al. 1999; Le Gal et al. 2011). Some models focus on one particular type of decision – mainly strategic (Barbier and Bergeron 1999; Berge and Ittersum 2000; Hyytiäinen et al. 2011) or operational (Martin-Clouaire and Rellier 2006; Merot et al. 2008; Martin et al. 2011a; Aurbacher et al. 2013; Moore et al. 2014). Some others model two decision levels – strategic and tactical (Trebeck and Hardaker 1972; Adesina 1991; Mosnier et al. 2009) or strategic and operational (Navarrete and Bail 2007; Dury 2011; Taillandier et al. 2012a; Gaudou and Sibertin-Blanc 2013). However, to the best of our knowledge, the scientific literature does not offer models that include a decision model with the three decision stages within the same model.

- How can we integrate adaptive behaviors in farmers' decision-making processes?

In the early 1980s, Petit developed the theory of the "farmer's adaptive behavior" and claimed that farmers have a permanent capacity for adaptation (Petit 1978). Adaptation refers to adjustments in agricultural systems in response to actual or expected stimuli through changes in practices, processes and structures and their effects or impacts on moderating potential modifications and benefiting from new opportunities (Grothmann and Patt 2003; Smit and Wandel 2006). Another important concept in the scientific literature on adaptation is the concept of adaptive capacity or capability (Darnhofer 2014). This refers to the capacity of the system to resist evolving hazards and stresses (Ingrand et al. 2009; Dedieu and Ingrand 2010) and it is the degree to which the system can adjust its practices, processes and structures to moderate or offset damages created by a given change in its environment (Brooks and Adger 2005; Martin 2015). For authors in the early 1980s such as Petit (1978) and Lev and Campbell (1987), adaptation is seen as the capacity to challenge a set of systematic and permanent disturbances. Moreover, decision-makers integrate long-term considerations when dealing with short term changes in production. Both claims lead to the notion of a permanent need to keep adaptation capability under uncertainty. Holling (2001) proposed a general framework to represent the dynamics of a socio-ecological system based on both ideas above, in which dynamics are represented as a sequence of "adaptive cycles", each affected by disturbances. Depending on whether the latter are moderate or not, farmers may have to reconfigure the system, but if such redesigning fails, then the production system collapses. Adaptive behaviors in farming systems have been considered (modeled) in bio-economic and bio-decision approaches. Formalisms describing proactive behavior and anticipation decision-making processes and formalisms representing reactive adaptation decision-making processes are used to model farmers' decision-making processes in farming systems. There is a need to include adaptation and anticipation to uncertain events in modeling approaches of the decision-making process.

- How can we represent interactions between different dimensions of decision-making processes?

Some of the most common dimensions in adaptation research on individual behavior refer to the timing and the temporal and spatial scopes of adaptation (Smit et al. 1999; Grothmann and Patt 2003). The first dimension distinguishes proactive versus reactive adaptations. Proactive adaptation refers to anticipated adjustment, which is the capacity to anticipate a shock (change that can disturb farmers' decision-making processes); it is also called anticipatory or ex-ante adaptation. Reactive adaptation is associated with adaptation performed after a shock; it is also called responsive or ex-post adaptation (Attonaty et al. 1999; Brooks and Adger 2005; Smit and Wandel 2006). The temporal scope distinguishes strategic adaptations from tactical adaptations, the former referring to the capacity to adapt in the long term (years), while the latter are mainly instantaneous short-term adjustments (seasonal to daily) (Risbey et al. 1999; Le Gal et al. 2011). The spatial scope of adaptation opposes localized adaptation versus widespread adaptation. In a farm production context, localized adaptations are often at the plot scale, while widespread ones concern the entire farm. Temporal and spatial scopes are easily considered in farmers' decision-making processes; however, incorporating the timing scope of farmers' adaptive behavior is a growing challenge when designing farming systems.

Conceive a flexible and resilient agricultural production system

- How can we design agricultural production systems from field observations?

The agricultural research community has a particular interest in modeling farming systems to simulate opportunities for adaptation that ensure flexibility and resilience of farming systems. To account for actors and their actions in the environment, it is essential to precisely represent their decision-making processes. Some methods have been developed to describe farmers' decision-making processes such as the "model for actions" (Aubry et al. 1998a), rule-based models (Bergez et al. 2006; Donatelli et al. 2006) and activity-based models (Clouaire and Rellier 2009; Martin et al. 2013). However none precisely specifies the process between farmers' decision-making and the modeling activity. There is no clear guiding framework explaining how to proceed from field studies to designing a model.

- Which representation should be used in conceptual modeling of farming systems?

A conceptual model is a non-software description of a computer simulation model. It is the bridge between the real system and a computer model (Robinson 2008) and therefore requires simplification and abstraction (Robinson 2010). We identified three main ideas in the scientific literature that are interesting to consider when modeling a farming system: i) a systemic representation is relevant (Martin et al. 2011b; Tanure et al. 2013), ii) dynamic processes bring the farming system to life (Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010), and iii) farmers' decision-making processes are flexible and adaptive over time and space (Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014). However, to the best of our knowledge, there is no representation of farming systems that integrates these three aspects into a conceptual model.

- How should the conceptual representation of farming system be implemented for computerized simulation?

Conceptual modeling is followed by software implementation that codes the conceptual results. In the past decade, several conceptual generic frameworks have been proposed for farm systems modeling (Bergez et al. 2013). To overcome problems which arise when building, simulating and reusing models (Reynolds and Acock 1997; Acock et al. 1999), generic computing platforms have been created to propose model repositories to facilitate their use and re-use (e.g. CropSyst (Van Evert and Campbell 1994) or ICASA (Bouma and Jones 2001)). The RECORD integrated modeling platform gathers, links and provides models and companion tools to answer new agricultural questions (Bergez et al. 2013). Coupling models representing the different entities of our agricultural production system should be facilitated by the use of such platform.

Consider a context of water scarcity and climate change

- How can we account for the effect of groundwater level on farming practices and simulate the retro-action of farming practices and in particular irrigation, on the variability of the aquifer?

In the Berambadi watershed, groundwater transmissivity and borewell yields decrease with water table depth (Maréchal et al. 2010). As a consequence, continuous pumping leads to severe water table drawdowns especially in hard rock aquifers and reduces the availability of groundwater for irrigation (Dewandel et al. 2010; Perrin et al. 2011). This feedback makes predefined land-use scenarios unrealistic, since farmers need to adapt their actions continually according to groundwater availability (Ruiz et al. 2015). Water table levels display a pattern that is atypical in hydrology: valley regions have deeper groundwater table levels than topographically higher zones. Thus, an unusual groundwater level gradient is observed; with a shallow groundwater table upstream and deep groundwater table downstream (Figure 1.3). This pattern results from intensive groundwater pumping since the early 1990s in villages located in the valley (where soils were more fertile) (Sekhar et al. 2011). Low costs of pumping water and subsidies for irrigation equipments encouraged farmers to drill even more borewells (Shah et al. 2009). This dramatic evolution is closely linked to the spatial distribution of soil type and groundwater availability, as well as farming practices, access to the market, new agricultural technologies and technical know-how, and government aid (Sekhar et al. 2011). Modeling how farmer practices depend on groundwater availability and how the global impact of pumping, farming practices and climate change impact on groundwater variability is important to understand the retro-action dynamic between practices and natural resource in particular.

A) Stream drainage and depth to groundwater level	B) Topographic elevation and water table level

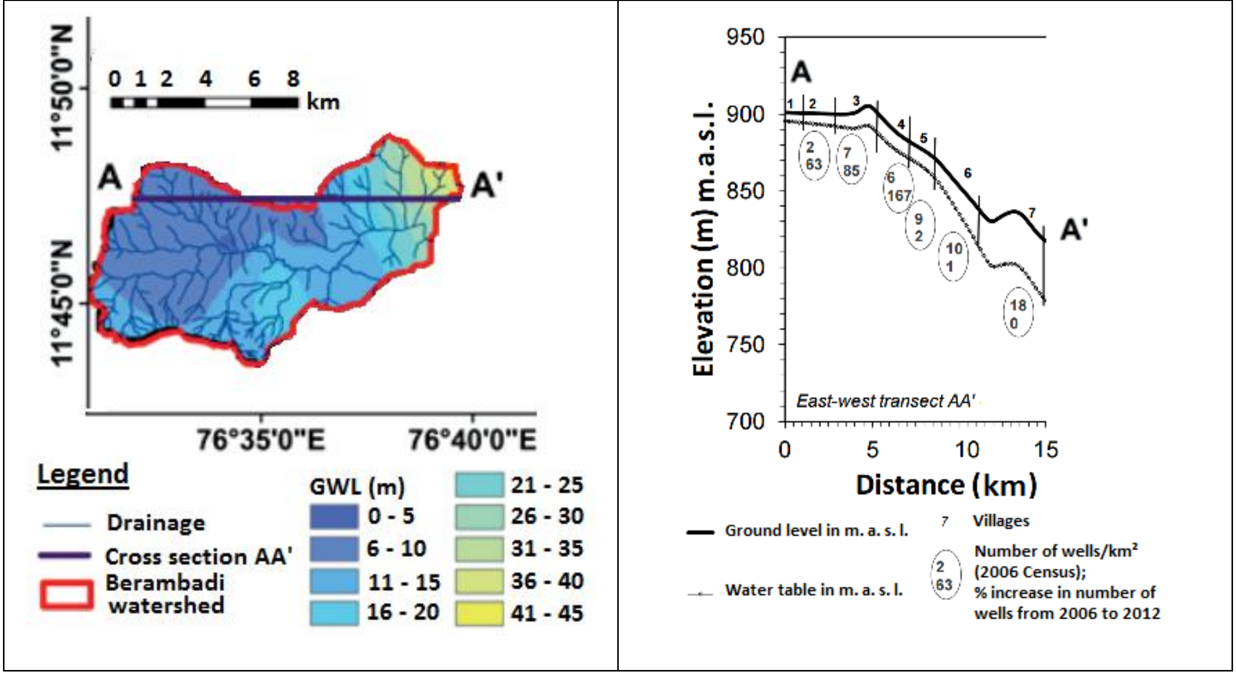

Figure 1.3 Groundwater level (GWL) in the Berambadi watershed. A) Stream drainage and depth to groundwater level, B) topographic elevation and water table level.

- Which scenarios should be tested for water management policies?

The motivation is to assess the future level of groundwater in the Berambadi watershed. The challenge is then to identify, design, and evaluate policies that encourage a better management of groundwater by farmers in a context of climate change. In concrete terms this means the adoption of alternative management options or adaptations that can be achieved at minimal social cost. Essentially, there are two types of instruments that may be adopted by policy makers. The first type encompasses quantity-control instruments, such as norms or quota-based instruments that limit the withdrawals of groundwater. The second type includes price-based instruments such as taxes or, conversely, subsidies intended to encourage the adoption of good practices and technologies. Price-based instruments act as incentives to reduce water use.

The first part of this thesis project focused on establishing a state-of-the-art of modeling approaches in agricultural systems, by taking into account the adaptation in the decision-making process of the farmer. The second phase of the thesis aimed to analyze real operating systems in order to achieve a conceptual modeling. Given the lack of stabilized methodologies in the scientific literature, it was necessary to establish a methodology to move from case studies to the conceptual based model. The last phase of the thesis allowed the passage of the conceptual model to the computer implementation. This computer model was used to simulate scenarios of climate change and water management policies in order to identify farmers' leverages and policy instruments to face these changes.

1.3. THESIS PROCEEDINGS

The main steps of the thesis can be summarized by the spiral cycle for the development of expert systems of Boehm (1988). The development of the simulation model NAMASTE (Figure 1.4) began with the expression of the needs formulated by the AICHA project to agree on what should be done in the model. An analysis of these needs helped formulating the project definition. Following the literature review (Chapter 2) and familiarization with the Berambadi basin (Chapter 3), we considered that the analysis and modeling of agricultural production systems in uncertain environment require taking into account the whole process of farmers' decisions in integrating the different temporal and spatial scales of decision making.

The conceptual model design formalizes the problem and chooses the functional specifications of the simulation model using a conceptual framework (Chapter 4 and 5). The farm was formalized with three entities (the decision-making system, the operating system and the biophysical system 3.4). The decision-making system has been described with the beliefs, desires, intentions formalism (BDI). The conceptual model was formulated in UML graphics to facilitate understanding between researchers, modelers, IT professionals and stakeholders of the project.

Conceptual modeling is followed by the computer implementation of the model on a simulation platform. Software development is done by coding the results of the design and functionality of the model highlighted in the previous steps. A first computer approach provides the economic decision model. A second computer approach adds the operation decision model coupled to the whole system.

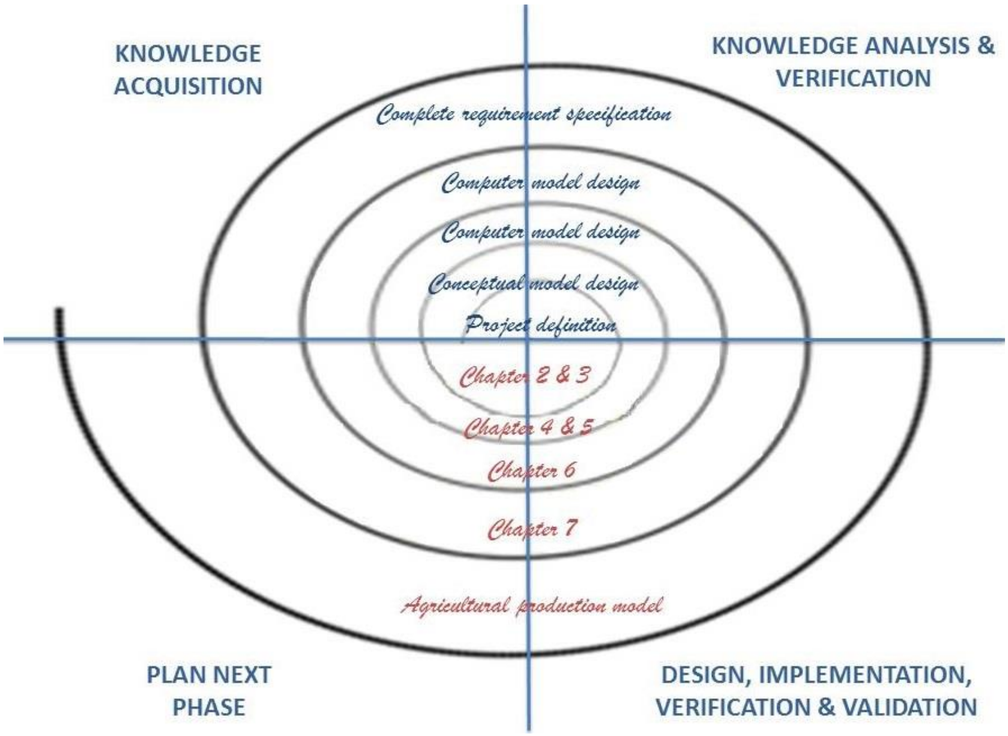

Figure 1 4 : Main steps of the thesis inspired by the spiral cycle of Boehm (1988).

1.4. THESIS RESULTS

1.4.1.Literature review on adaptation in decision models

Agricultural production systems are facing new challenges due to a constantly changing global environment that is a source of risk and uncertainty, and in which past experience is not sufficient to gauge the odds of a future negative event. Concerning risk, farmers are exposed to production risk mostly due to climate and pest conditions, to market risk that impacts input and output prices, and institutional risk through agricultural, environmental and sanitary regulations (Hardaker 2004). Farmers may also face uncertainty due to rare events affecting, e.g. labor, production capital stock, and extreme climatic conditions, which add complexities to producing agricultural goods and calls for re-evaluating current production practices. To remain competitive, farmers have no choice but to adapt and adjust their daily management practices (Hémidy et al. 1996; Hardaker 2004; Darnhofer et al. 2010; Dury 2011). Facing the aforementioned challenges, conventional farming systems have their limitations and a particular attention is made on the dynamics of innovations likely to consider and resolve the former issues (Novak 2008). The agricultural research community has a particular interest in modeling farming systems to simulate opportunities for adaptation that ensure flexibility and resilience of farming systems. In this context of global change, it is important to include adaptation to model farmers' decision-making processes.

To review the way adaptive behaviors in farming systems has been considered (modeled) in bio-economic and bio-decision approaches; we analyzed approximately 40 scientific references. This work reviews several modeling formalisms that have been used in bio-economic and bio-decision approaches, comparing their features and selected relevant applications. We chose to focus on the formalisms rather than the tools as they are the essence of the modeling approach (Figure 1.5).

The major points are: adaptability, flexibility and dynamic processes are common ways to characterize farmers' decision-making. Adaptation is either a reactive or a proactive process depending on farmer flexibility and expectation capabilities. Various modeling methods are used to model decision stages in time and space, and some methods can be combined to represent a sequential decision-making process. Sequential representation is particularly interesting and appropriate to model the entire decision-making processes from strategic to tactical and operational decisions. Strategic adaptations and decisions influence tactical adaptations and decisions and vice-versa. Decisions made at one of these levels may disrupt the initial organization of resource availability and competition among activities over the short term (e.g., labor availability, machinery organization, irrigation distribution) but also lead to reconsideration of long-term decisions when the cropping system requires adaptation (e.g., change in crops within the rotation, effect of the previous crop). In the current agricultural literature, these consequences on long- and short-term organizations are rarely considered, even though they appear as an important driver of farmers' decision-making (Daydé et al. 2014). Combining several formalisms within an integrated model in which strategic and tactical adaptations and decisions influence each other is a good starting point for modeling adaptive behavior within farmers' decision-making processes.

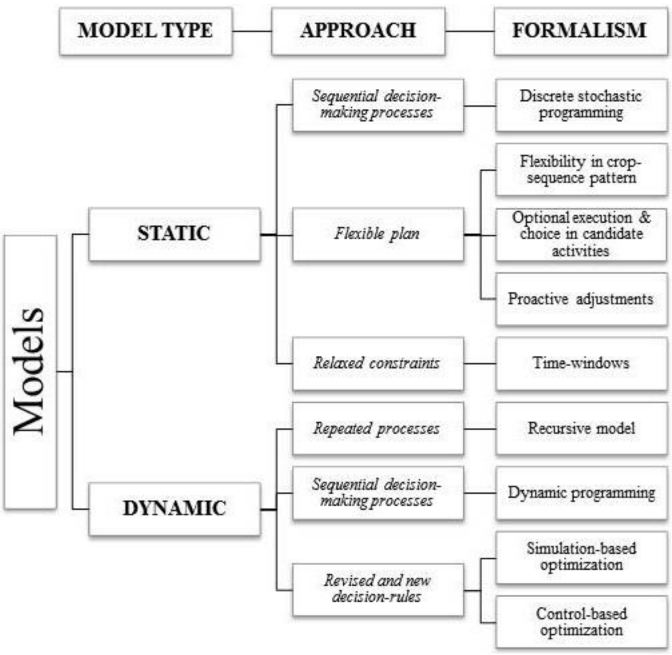

Figure 1.5 : Typology of models to manage adaptive decision-making processes according to model type, approach, and formalism.

1.4.2.The Berambadi watershed

In semi-arid regions, agricultural production systems depend greatly on irrigation and encounter increasing challenges: growing uncertainty about response to climate change, severe depletion of natural resources, high price volatility in agricultural markets, rise in energy costs, greater pressure from public regulations (agricultural, environmental and health policies), and conflicts about sharing common water resources. Modeling farming systems while accounting for their flexibility is needed to assess water management policies targeted for specific geographical areas.

While modeling farming systems for assessing the development of such targeted water management policies, typifying farming systems is a fundamental step (Köbrich et al. 2003). Indeed, modeling all individual farms within a territory is rarely feasible if the number of farms is large and if the distribution of farming systems is heterogeneous. Typologies have been presented as a convenient tool to simplify the diversity of farming systems while effectively describing their heterogeneity (Valbuena et al. 2008; Daloğlu et al. 2014). As farm types are adapted to local constraints such as resource availability, the identification of their spatial distribution or location factors is also needed (Clavel et al. 2011).

Farmers' investment decisions in irrigation and adopting cropping systems are inherently dynamic and are modified by changes in climate and agronomic, economic and social, and institutional conditions. To represent this diversity, we developed a typology of Indian farmers from a survey including 684 farms in Berambadi. The questionnaire answers provided information on the farm structure, cropping systems and farm practices, irrigation water management, and the economic performances of the farm. Descriptive statistics and multivariate analysis (Multiple Correspondences Analysis and Agglomerative Hierarchical Clustering) were used to analyze the relationships between observed factors,and to establish the farm typology. We identified three main types of farms: 1) large, diversified and productivist farms, 2) small and marginal rainfed farms, and 3) small, irrigated marketing farms (Figure 1.6). This typology represents the heterogeneity of farms in the Berambadi watershed. Used within a simulation model for the watershed, this typology should enable policy makers to better assess the potential impacts of agricultural and water management policies on farmers' livelihood and groundwater table.

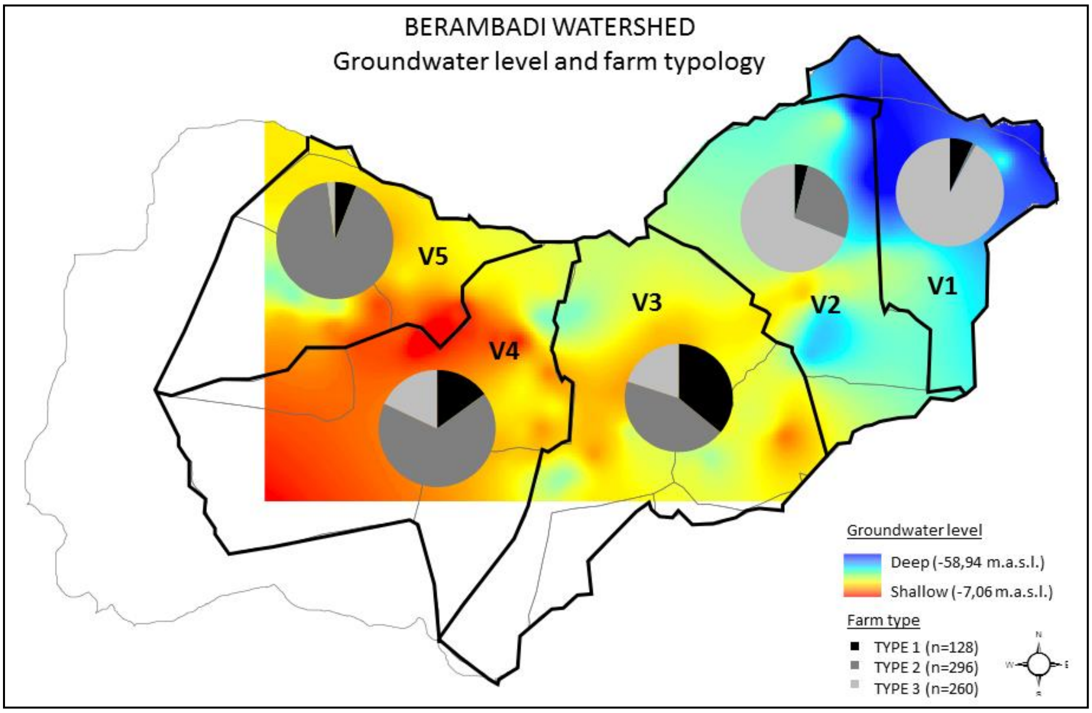

Figure 1. 6: Groundwater table gradient (colors) and farm typology (pir chart) for each of the five villages (V1 to V5) on the Berambadi watershed. TYPE 1 is large, diversified and productivist farms; TYPE 2 is small and marginal rainfed farms; and TYPE 3 is small, irrigated marketing farms.

1.4.3. A methodology to guide the design of a conceptual model of farmers' decision-making processes

The agricultural research community has a particular interest in decision-making processes design in farming systems but does not have a clear framework to guide it in how to proceed from field studies to designing the conceptual model. We identified a gap between field observations and the design of a conceptual decision model by modelers. Thus, we provide a necessary, original, and useful step-by-step methodology that guides data acquisition and analysis, incorporation of farmers' knowledge, and model design. Developing a methodology for model design is necessary to ensure model transparency. It is essential to include information about the process followed to develop the conceptual or simulation model. This helps reproduce the work so that future researches can test any insights found or replicate the process in another study.

We propose an original and readily applicable methodology to formalize the conceptual modeling of the farmer agent underlying decision-making processes in farming system (CMFDM) and to guide data acquisition and analysis, the incorporation of expert knowledge, and the design of a model. The methodology combines techniques for system description based on field research in natural settings and techniques from the software engineering field regarding the use of software engineering language to support the development of a model. Theory building from cases is used to obtain a relevant theory from observing actual practices in a natural setting (Glaser and Strauss 1967; Eisenhardt 1989; Yin 2013). Cognitive-Task Analysis (CTA) is used to analyze and model the cognitive processes that gave rise to farmers' task performance in farming systems (Jonassen 1997; Chipman et al. 2000). Unified

Modeling Language (UML) is used to represent the decision-making problem in a standard and readily usable form for computer programming (Booch et al. 1996; Papajorgji and Pardalos 2006).

Our methodology is made of four steps (Figure 1.7):

- The first step is problem definition with the definition of the context and the initial research question.
- The second step consists in selecting the population likely to exhibit the research focus and select the case studies. As in statistical research, it is essential to control variations and define the limits of the generalization process.
- The third step is data collection and analysis of individual case studies.
- The last step is the transition from individual case studies to a generic model. It is an iterative process of cross-cases analysis, enfolding of literature, and incorporation of expert knowledge.

The case-study approach enables building a conceptual model with a higher level of refinement than statistical methods. Statistical studies combine dissimilar cases to obtain a large sample and run the risk of conceptual stretching (George and Bennett 2005), whereas case studies can reach a high level of validity with a smaller number of cases. Combining both a bottom-up (from farmers) and a top-down (from experts and modelers) approach is a pragmatic way to develop consistent and reusable models based on shared concepts (Milton and Shadbolt 1999; Beck et al. 2010). We used UML as a unique formal language that facilitates iterations and feedback between different methodological steps. It also ensures consistency and transparency during the process from knowledge transcription to decision-model application.

Our research may provide a useful tool for modelers looking for clear guidance on how to build the agent sub-model in a farming system model.

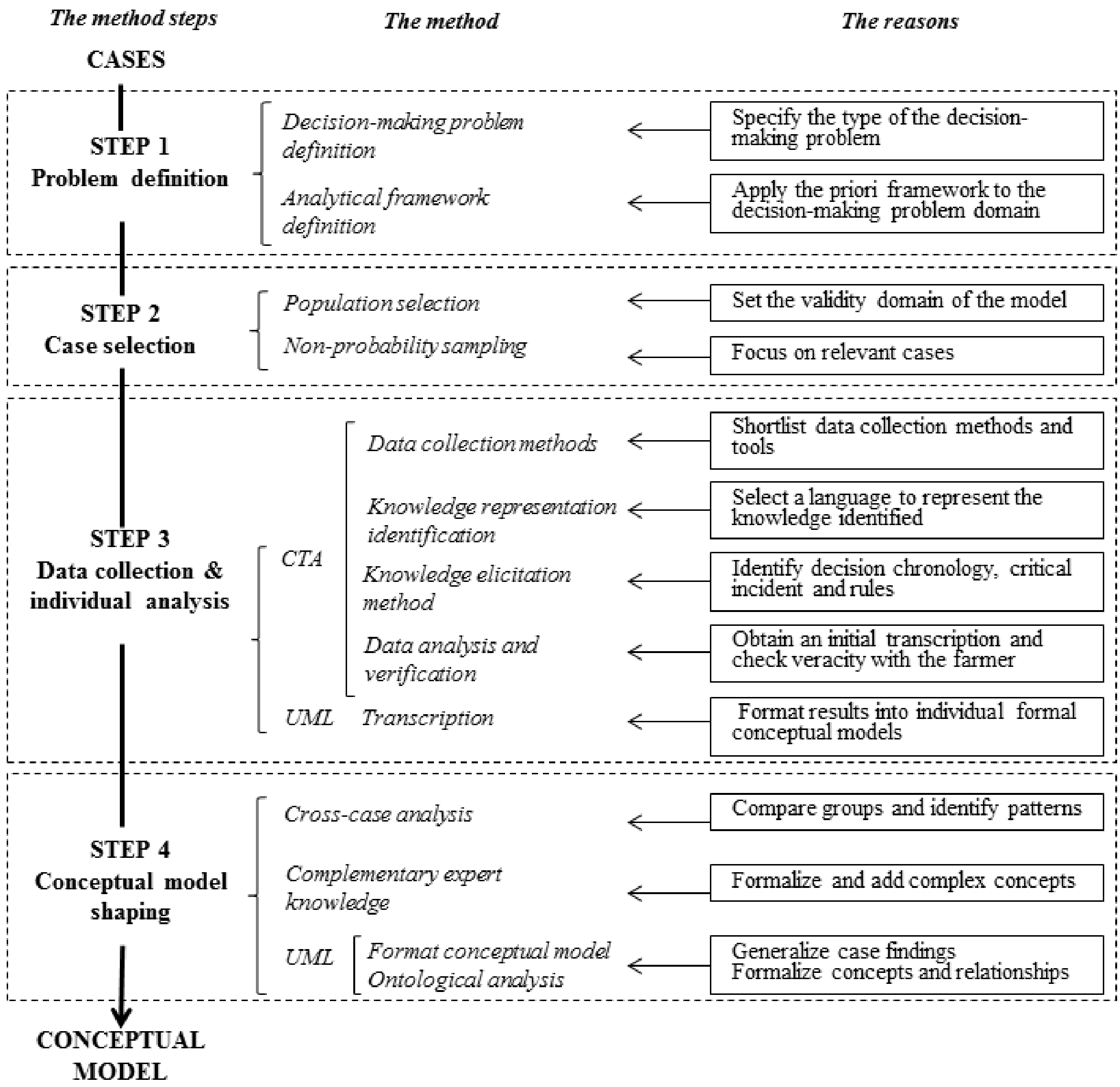

Figure 1.7 : The four methodological steps to conceptualize a farming systems and to guide data acquisition and analysis, integration of expert knowledge, and computer implementation.CTA=Cognitive Task Analysis, UML = Unified Modelling Language.

1.4.4. The conceptual model NAMASTE

We identified three main ideas in the scientific literature that are interesting to consider when modeling a farming system: i) a systemic representation is relevant (Martin et al. 2011b; Tanure et al. 2013), ii) dynamic processes bring the farming system to life (Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010), and iii) farmers' decision-making processes are flexible and adaptive over time and space (Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014). We developed an original representation of farming systems that integrates these aspects into a new conceptual model (Figure 1.8).

The production system is divided into three interactive sub-systems: i) the decision sub-system (manager or agent), which describes the farmer's decision process as a combination of knowledge about the system, objectives, and decisions; ii) the operating sub-system (technical system), which translates the decision orders into action execution and dynamics of farm resources; and, iii) the biophysical sub-system, which describes interactions between physical and biological items, in particular the relations between ground water, soil, and plant growth and development (Clouaire and Rellier 2009; Le Gal et al. 2010; Dury 2011; Akplogan 2013). We considered farmers as cognitive agents able to think, memorize, analyze, predict and learn to face future events and plan their actions (Le Bars et al. 2005). We used the as Belief-Desire-Intention (BDI) framework to represent this cognitive agents (Bratman 1987a; Rao and Georgeff 1991).

One original feature of our model is the decision sub-model that covers three stages of decisions and adaptations:

- Each year, farmers decide whether to invest in irrigation equipment (e.g. dig a new borewell, get a new pump) to optimize their profit. They also select the corresponding cropping system and associated crop management operations (e.g. land preparation, sowing, fertilization, irrigation, harvest) that will ensure the best income for their long-term climatic and price expectations. This decision stage has a long-term effect on the entire farm due to the long duration of loans and equipment life.
- Each season, farmers make a decision that will have a medium-term effect on the entire season and establishes the cropping system adopted for the season. Farmers integrate new observed knowledge about climate and prices so that the cropping system initially selected at the beginning of the year may no longer best optimize their income. They review their crop selection and match the best practices to obtain the best cropping system for the known farming conditions.
- From the cropping system selected at the beginning of the season, farmers decide and adjust their daily crop operations in each plot depending on climate conditions and resource constraints. This decision stage covers the entire season at a daily time step

To model three stages of decision, we combined economic, decision-rule, and activity-based models. Sequential representation is particularly interesting and appropriate to model the entire decision-making processes from strategic to tactical and operational decision (Risbey et al. 1999; Le Gal et al. 2011). Another original feature is the integrated dynamic interaction of different sub-systems that build the farm production system.

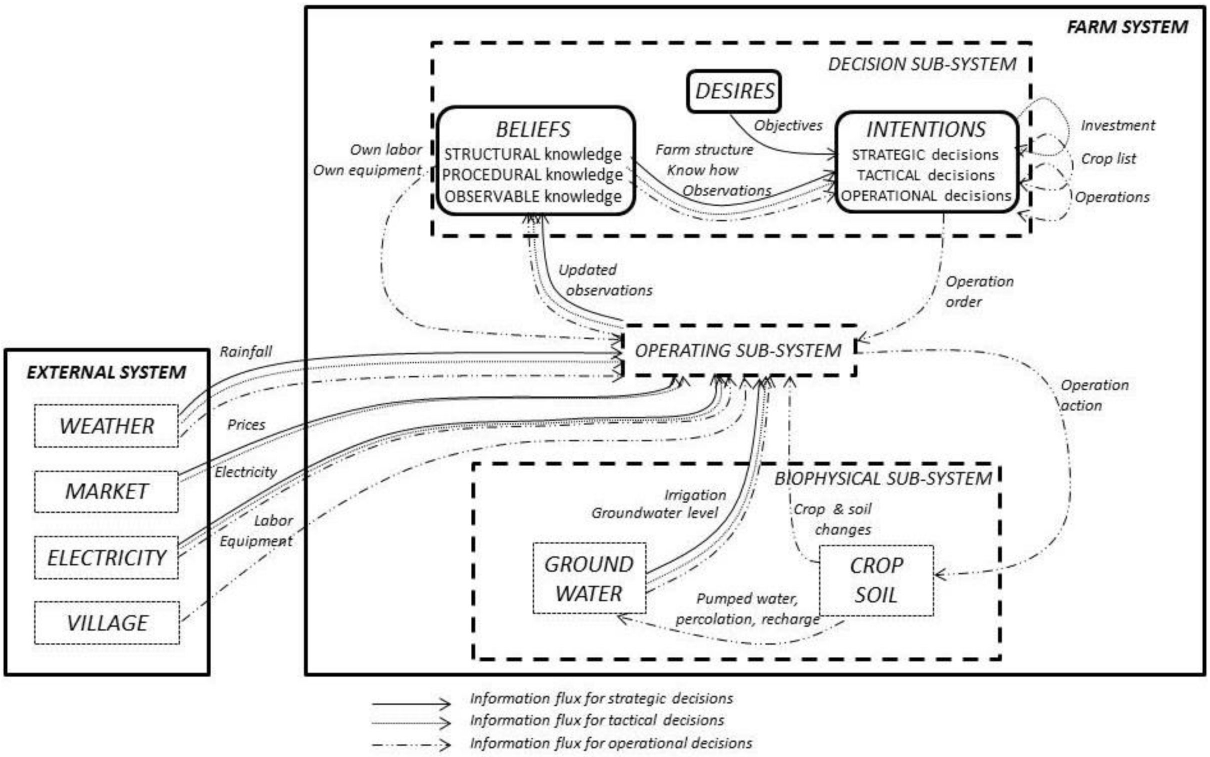

Figure 1.8 : The farming system as a Decision-Operating-Biophysical System framework. Presentation of the sub-models used in the conceptual model. The Beliefs, Desires, and Intentions framework provides structure to the decision sub-system. It breaks the system down the system into these three entities, each composed of several items. Beliefs are composed of structural, procedural, and observable knowledge, as well as strategic, tactical and operational intentions (adapted from Rao & Georgeff, 1991). Dynamic flow of information exchanged during the decision-making process from strategic to tactical and operational decisions.

1.4.5. Strategic decisions on investments and cropping systems modeled with a stochastic dynamic programming approach

Long-term investment decisions in borewell irrigation and on cropping system are modeled by a stochastic dynamic programming approach. The model is based on season-specific crop choice and medium-run (yearly) investment (or effort) decisions) in irrigation facilities (or capital stock). We assume that farmers optimize their profit over a long period of time and account for the consequences of today's decisions regarding investment in irrigation on future water availability (because the latter ultimately determines future crop output, hence future profit flows). The fact that the farmer is allowed to decide both on crop allocation and irrigation investment makes the problem fully dynamic, because today's decisions on investment will affect water availability in future periods (years).

The objective function aims at selecting the investment in irrigation I_t and the cropping system c that maximizes the profit π of the farmer based on expectations on rainfalls, available water for irrigation W_t, crop price, crop costs, crop yields and crop failure:

$$\max_{\{I_t\}} \sum_{t=1}^{T} (1+r)^{-t} \left\{ \max_{\{\delta_{bc\tau}\}} \left[\sum_{b=1}^{B} \sum_{c=1}^{C} \sum_{\tau=S1}^{S2} \delta_{bc\tau}\, \pi_{bc\tau} \right] - I_t \right\},$$

where r is a constant discount rate, and $\delta_{bc\tau} = 1$ if crop c is grown on plot b at season τ and 0 otherwise.

The stochastic dynamic programming problem can be solved using a variety of methods. We assume here that, since no condition is imposed a priori on the terminal level of water availability or irrigation capital stock, we have an infinite horizon problem. A popular way of solving such infinite-horizon problem is the collocation method applied to the Bellman equation for dynamic programming.

It is well known that the problem above can be written equivalently in terms of a value function $V(W_t)$:

$$V(W_t) = \max_{I_t}\{\pi_t^*(I_t, W_t) + \beta\ E_{\tilde{R}} V(W_{t+1})\}, \forall t,$$

where $V(W_t)$ is the value function (the maximum of current and future revenues) with the state variable as its argument, whose (dynamic) transition equation is

$$W_{t+1} = f(W_t, I_t),$$

β is a discount factor and $\pi_t^*(I_t, W_t)$ is the current year's profit function.

This decision model is generic and independent of the rest of the NAMASTE global model. It allows producing marketable knowledge in other research contexts. For example, for NAMASTE this model is clibrated for farming systems in the hard rock aquifer of the Berambadi watershed. However, this model could also be used for areas of the Gangetic plain with alluvial aquifer.

The model was used to test water management policies aiming at limiting the groundwater table depletion under climate change. Three scenarios were tested: 1) subsidies for rainfed crops, 2) payment of electricity, 3) taxes on piezometric level. In condition of climate change, taxes on piezometric level are the best approaches to maintain the groundwater level (Figure 1.9) and limit the decline of farmers' profit (Figure 1.10).

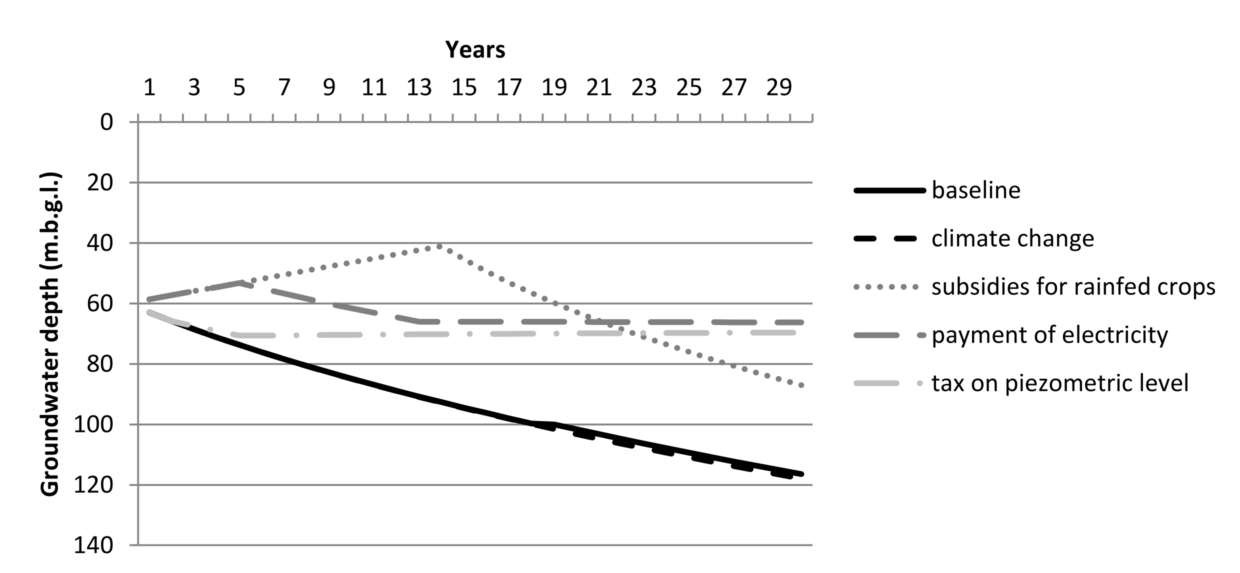

Figure 1 9 : Groundwater level over the planning horizon – baseline and scenarios results.

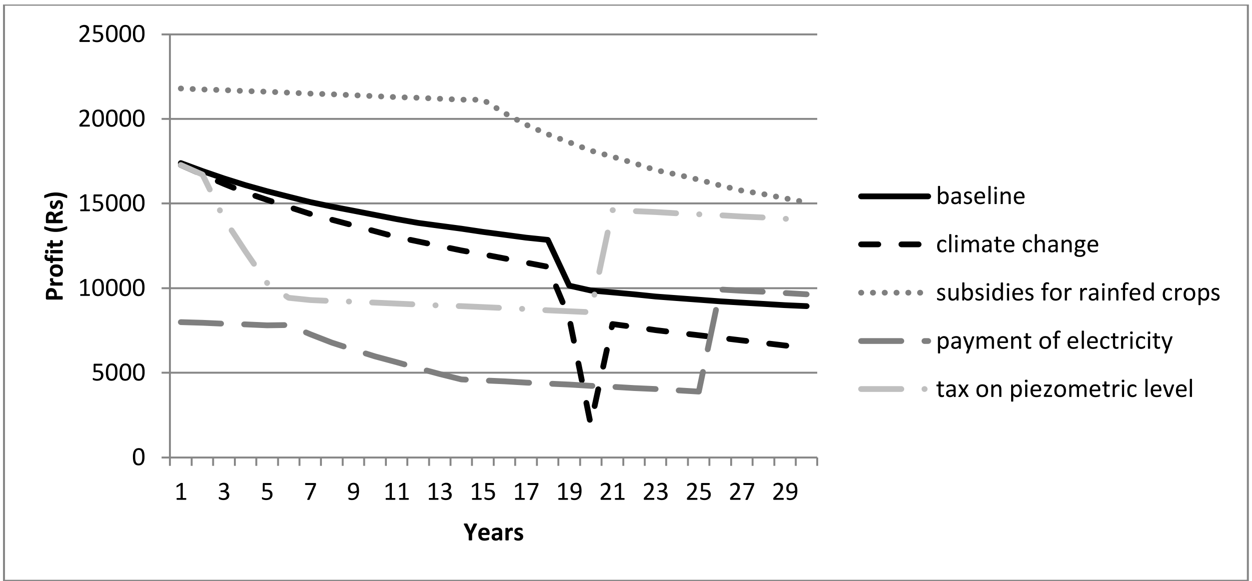

Figure 1.10 : Farmers' profit over the planning horizon – baseline and scenarios results.

Another common policy used on watershed for water resource management (e.g. the Beauce plain, Graveline (2013)) are individual quotas where farmers paid a tax for any volume of water pumped in addition to their initial quota. This approach will require a control of pumping with water meter which are not commonly present on the watershed. Future work may be on combining several water management policies.

1.4.6.The computer model NAMASTE

My last chapter presents the simulation model NAMASTE that model the interaction between investment and management decisions, the technical activities implemented on plots and biophysical processes in response to external factors such as weather, prices and availability of resources.

The implementation of the conceptual model was done using the modeling and simulation platform RECORD (INRA Toulouse) dedicated to the study of agro-ecosystems (Bergez et al. 2013; Bergez et al. 2016). The two main originalities of the NAMASTE model are: 1) the decision model that simulate farmers' decision-making processes describes dynamic sequential decisions with adaptation processes to the biophysical environment; 2) it couples decisional, economical, biophysical and hydrological systems in order to include the whole consequences and spillover of human decisions on natural systems. NAMASTE is used to simulate a virtual village of two virtual farms that share resources (equipment and labor) at different time frames (Figure 1.11).

NAMASTE simulates the decisions and adaptations of farmers at different time (strategic, tactical, operational) and space (from the farm to the plot) scales. It also represents the interactions between farmers for resource uses such as water, labor and equipment. The model emphasizes the feedback and retroaction between farming practices and changes in the water table (impact of pumping on groundwater availability and impact of water availability on farming practices).

Like many agent-based models that aim in representing a complete system (An 2012), coupling decisional, economical, biophysical and hydrological models was necessary to model and quantify the spatio-temporal variability of water resources and the interactions between groundwater on the one hand, and agricultural practices and crop growth on the other hand. The difficulty encountered was to associate independent models that were originally developed for a specific purpose at different space and time scales (Kraucunas et al. 2015). Calibrating and validating the global model is an important and time-consuming step that is still in process (we encountered 94 parameters directly accessible in the global model, AMBHAS (Assimilation of Multi-satellite data at Berambadi watershed for Hydrology And land Surface experiment – hydrological model) and STICS (Simulateur multidisciplinaire pour les cultures standard – crop growth model) also have numerous internal parameters that lead to tedious calibration).

Our model provides tools for analyzing, evaluating, and optimizing agronomic, environmental and economic criteria. We tested a baseline scenario to simulate current farming practices in the Berambadi watershed and predict their influences on the groundwater level for a virtual village made of two farms. Modeling agricultural production scenarios can effectively help stakeholders make decisions about regulations and resource restrictions and encourage new practices to be recommended to farmers.

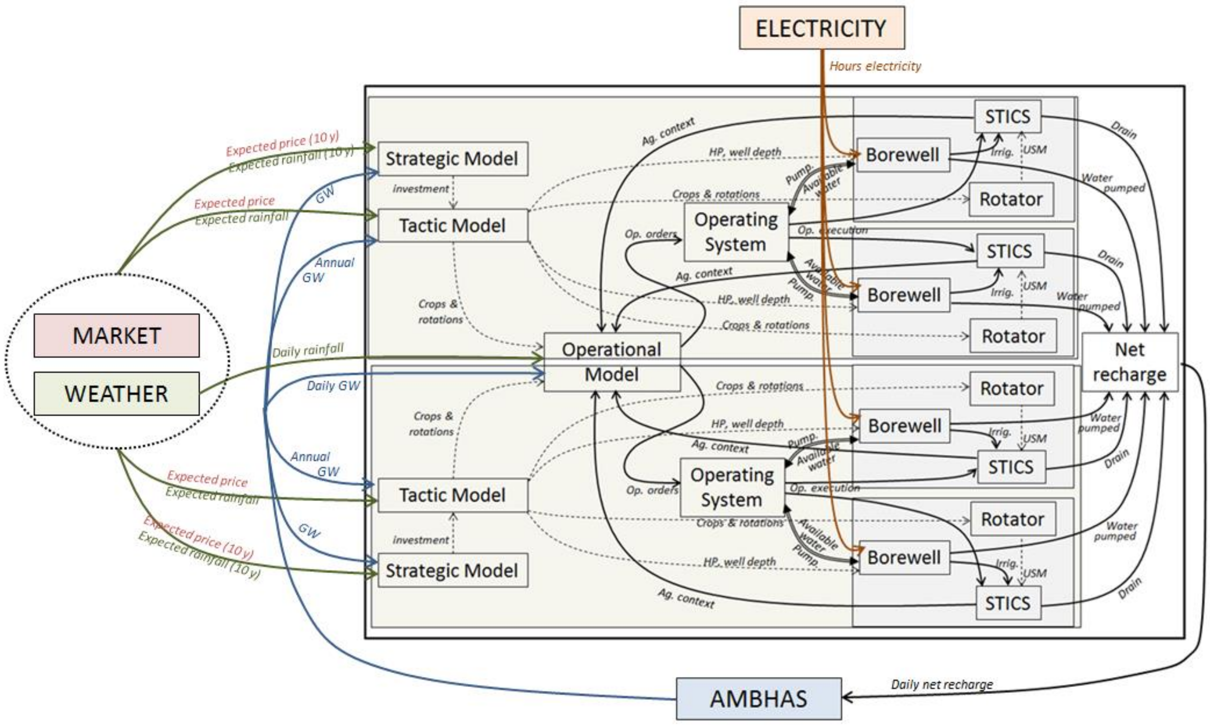

Figure 1.11 NAMASTE simulator - a virtual village composed of two virtual farms (F1 and F2) both having access to ground water on the same AMBHAS cell. Each farm is simulate by two individual DEVS atomic decision model (strategic and tactic) and a common operational decision model using the VLE decision extension of RECORD that describes individual operational decisions for the whole village. The WEATHER model, the MARKET model and the ELECTRICITY model constrain the same way both farms. P1, P2 are the plots of farm 1. P3, P4 are the plots of farm2.

1.5. Discussions and prospects

1.5.1. Review on the thesis results

The objectives of this thesis were to represent farmers' decision-making and adaptation processes, and conceive a flexible and resilient agricultural production system under a context of water scarcity and climate change. Following this work an operating model was proposed in order to meet some of the expectations of the AICHA project.

To illustrate the progress of the thesis, we refer the spiral cycle for the development of expert systems of Boehm (1988) presented in part 1.3. The spiral cycle therefore provides for the delivery of prototypes, e.g. incomplete versions of the product. Prototypes are considered as vertical prototypes where each prototype adds partially functional parts (Abdelhamid et al. 1997; Mosqueira-Rey and Moret-Bonillo 2000) (Figure 1.12).

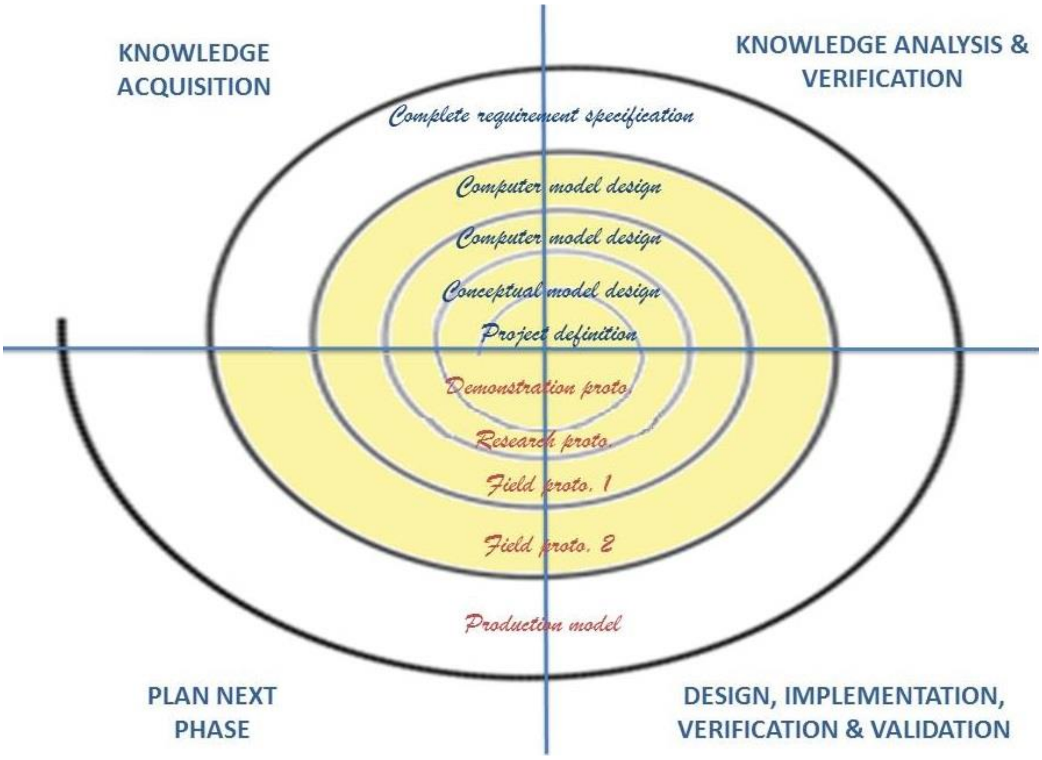

Figure 1.12 : The spiral cycle adapted from Boehm (1988) and the delivery of prototypes from demonstration prototype to production model. The yellow part corresponds to the progress of my thesis.

The thesis started by identifying the necessary knowledge to understand the operation of farms and decision-making processes of farmers. After a review of literature on adaptive behavior in farmers' decision-making processes (Chapter 2) and the familiarization with the case of Indian study (Chapter 3), we decided to take into account the whole process of farmers' decision and to integrate the different temporal and spatial scales of decision making. Thus in our Indian case, three types of decisions and various adaptation options have been identified taking place at three different levels (strategic, tactical and operational). These functional specifications led to a first demonstration prototype.

Then it was important to have the tools to organize and to integrate farming system knowledge into the production system design process. I set up a step-by-step methodology (Chapter 4), to move from case studies to a conceptual model. This conceptual model was used as research prototype. It precisely defined the processes I wanted to take into account to meet the thesis objectives and AICHA project expectations. The conceptual model presented in this thesis (Chapter 5) focused on the description and definition of the decision model in interaction with other models of the operating system and external system. This research prototype must be clear and understandable by all. The conceptual model is based on an ontology that provides a common vocabulary for all individuals involved in the project (researchers, modelers and experts). This allowed to discuss the model and to validate the model by the majority of participants of the AICHA project. This research prototype was the basis for the computer implementation of the model on the RECORD simulation platform. A first field prototype provides the economic decision model. A second field prototype adds the operation decision model coupled to the whole system. Functional tests have validated first each entity of the model independently before validating the entire model. The final field prototype that I obtained corresponded to a computer model useful to run scenarios of climate change, agricultural policy and resources scarcity and to identify the levers used by farmers to cope with these changes in a qualitative point of view. Improvements and deepening will be needed later to reach the production model that will meet the expectations of AICHA project.

1.5.2. From the demonstration prototype to the production model

Selecting the biophysical model

In farm systems, decisions are translated into technical operations impacting the biophysical system. These decisions are dependent on farmer's observations on the state of the biophysical system. Thus in NAMASTE, strategic and tactical decisions rely on crop yields while operational decisions depend on soil conditions, crop stage and germination rate. Technical operations impacting on the biophysical system are soil preparation, sowing, fertilization, irrigation and harvesting. Two major types of crop simulation models are often used: 1) empirical or statistical models that consider relationship between yields and components of yields with climate and environmental settings as correlation equation or regression ; and 2) the mechanistic or functional models that describe both the relationships and mechanisms between soil-plant systems, and climate decision (Basso et al. 2013). To simulate daily and dynamically plant growth, use of water and crop management operations, we selected the mechanistic model STICS to be coupled with our decision model (Brisson et al. 1998).

Three main limitations are identified:

1) Even if STICS is meant to be a generic crop model able to simulate several types of crops, its calibration is difficult and brings a significant amount of uncertainty concerning the validity of the model.
2) STICS does not take into account biotic processes such as pests, diseases and weeds that have a significant impact on plant growth (Bergez et al. 2010).
3) Crop rotation is not directly considered in STICS. The crop model must be coupled with a crop rotation model that loads a simulation unit for each new cultural plan launched by the decision model.

The simplest alternative would be to consider the yield and the water used as the only parameters to be considered in the decision, instead of simulating the dynamic aspect of the model. This approach is acceptable for the strategic and tactical decisions as they are based on an expected average yield and average production costs. However it is not acceptable for operational decisions because the conditions of the technical operations depend on these dynamic crop settings. In this case, only the rain and the availability of resources should constrain the decision to run a technical operation. Other simplified functional models and calibrated for Indian crops exist as AquaCrop FAO (Raes et al. 2011) but are based on a single process e.g. the water balance and exclude other environmental outputs e.g. nitrogen and carbon footprints and the biotic and abiotic stresses affecting yields.

The decision model: an integrated model?

The sequential representation is particularly suited to represent the whole decision making process from strategic decisions to tactical and operational decisions (Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010). The strategic decisions influence the tactical and operational decisions and vice versa disrupting the availability of resources and generating competition between activities in the short term but also by challenging rotations and crop sequences (Daydé et al. 2014). The description of these processes requires the development of a decision model at three levels built like we proposed in NAMASTE. However, the current model does not fully describe this integration. Starting from independently developed models, there remains some work regarding the coupling of the different levels of decisions to make the global model dynamically integrated.

Strategic and tactic decisions are based on farmer’s expectations on events, occurrences, levels of certain variables and parameters affecting decisions. Each new piece of information received may impact farmers’ expectations and makes them reconsider and review their expectations. For instance, the strategic decision model is mainly based on climate, market prices, production costs and yields expectations. Through learning and appropriation processes of observed information, farmers review their expectations by integrating it to their own knowledge database. This implies that observed information at operational level are dynamically transferred to the farmer's knowledge database and integrated into the algorithm that formulates farmer’s expectations. For example, in our strategic decision model the farmer refers to probabilities of occurrence of year more or less rainy set by the last 40 years of climate data. Running the operational decision model with new climate data is not going to change the probabilities of occurrence at the strategic level. The model should dynamically integrate the new information in its formalism to compute these probabilities of occurrence. Bayesian approaches are commonly used for the revision of parameters in dynamic systems (Stengel 1986). Concerning yields, a higher level of integration could be expected between economic and operational models and between tactical and operational models. At the strategic level, yields are currently estimated from simple production functions depending on level of irrigation and are calibrated for several climate occurrences. Given the use of a functional crop model for the operational level it is unfortunate that we did not to include it in the upper levels to obtain yields. Thus each loop testing crop profits should use the operational level over many representative years to obtain an average yield which would include the intra- seasonal variability of rainfalls.

The decision model: a generic model?

In order to model the different types of farms identified in Chapter 3, some parameters of the NAMASTE model must be made more generic and flexible. A critical point is the possible change of number of plots of a farm within a planning horizon. Indeed, changing the number of plots should automatically change the structure of the strategic and tactic models in terms of possible iterations and crop combinations. It should also change the operational model by adding plots (or STICS models) and linking them to the operating system and the corresponding decision model.

Another issue that deals with the possible change of number of plots is the management of the soil characteristics from year to year. Soil status is simulated by the STICS models. Right now, we consider that at each simulation the hydrological and mineral state of the soil is re-initiated to the initial conditions. However, technical practices and crop types impact on soil status. When plot sizes and plot number are fixed, it is easy to take in consideration these year-to-year impacts. However, when plots are changing, it becomes difficult to know from which STICS model should the values come from.

Also calibration of new crops will allow better describing farm types depending on rainfed and irrigated conditions or on crop objectives of sale or self-consumption. For now, it is the irrigated farms with cash crops that are the best addressed in NAMASTE.

Finally, the generic characteristic of the structure and formalisms used in this model depend on the ease to use it in other cases studies. The systemic representation is suitable for any type of farm system where the farm is considered made of a decision component in interaction with a biophysical component under variable and uncertain environment conditions. The structure and sequential representation of the farmers' decision-making processes is also generic and reusable in other contexts. Other combinations of strategic / tactical / operational decisions can be described with this approach. However, the adaptation to other case studies requests a facility on the instruction of new decision rules and constraints. With today' model, these adaptations are possible but require precise documentation on the steps and methodologies to implement.

Improvements and deepening for the NAMASTE model

Climate scenarios and water management policies have been tested during my thesis. However many improvements in the computer implementation are possible and could not be done during my PhD for lack of time. First to reconsider the points made in the previous paragraph, farm structure and initialization parameters are not fully scalable. Later on, the model will be able to dynamically create one or more farms from an input file.

Second, the technical management practices (ITK) are described in csv files, read by an R script that turns them into plan files mobilized by the RECORD decision plugin. For the same crop, several ITK are possible depending on the intensification of practices in terms of fertilization and irrigation. Howeverr, given the current model architecture, each ITK is also specific to the operation through the resources (labor and equipment) to be mobilized for the execution of technical operations. Thus there are currently nearly 100 plan files (5 x 10 crop intensification practices x 2 farms) to load at the beginning of each simulation which dramatically slows down the simulation process. Subsequently, the plan file creation should be dynamic so that plan files are not specific to farms (in terms of resources) and that only those mobilized for the simulation are loaded in the simulator.

The duration of technical activities is also a point on which modeling time should be spent. So far, the simulator considers that each activity takes place in one day and systematically releases resources for the next day. However, certain activities such as sowing, weeding and harvesting can take place over several days depending on the availability of the workforce. Subsequently, the operating system should be able to set the duration of a technical activity depending on the resource needs and on the available resources. It should also maintain the mobilization of resources during the whole activity duration.

To deal with the issue on soil state and plot changes, one solution may be to sub-divide a farm into smaller-sized sub-plots. Then a plot will be a combination of sub-plots and will have several STICS models running independently to simulate a crop growth.

Moreover, the management of alternative crops at a sowing or germination failures does not allow to reuse the initial rotation as the replacement crop is added to the rotation, which implies that the rotation is modified and subsequently integrates the alternative crops. However a rotation is assumed to be fixed. Even if adjustments are possible during rotation they should not be maintained for the next rotation. The management of the rotation is done at two levels: 1) at the decision level, 2) at the biophysical level. The problem lies in the biophysical system. The rotator is a model in charge to load the subsequent simulation unit (USM) for the STICS model. At the beginning of the simulation, the same crop list is provided to the decision model and the rotator. When the replacement crop is introduced, the rotator receives an alert from the decision model to inform him about the replacement of one culture by another. The rotator will then insert this new crop in its crop list but is not able to identify this new crop as a temporary crop.

Finally, the setting of the model makes it difficult to test alternative scenarios in terms of new practices and policies. Indeed, the setting of crops under STICS is tedious and requires a lot of field data. Integrating new ITK requires describing new decision rules, new predicates, and new constraints. Add a new policy requires changing the script and the parameter files of the strategic and tactic model.

1.5.3. Verification and validation

Verification and validation in the model development process

Each prototypes developed during the development cycle of the agricultural production system is followed by verification and validation phases to obtain a valid simulation model (Borenstein 1998; Sargent 2013; Augusiak et al. 2014) (Figure 1.13). Conceptual validation follows the development of the conceptual model (or research prototype) and this process is repeated until the conceptual model is sufficient to meet the objectives of the initial problem and its modeling. The verification of the computer models ensures that the computer models (field prototype 1 and 2) are correctly implemented in relation to the conceptual model. Finally the operational validation is conducted on the computer model to determine if the outputs of the simulation are adequate for simulation purposes. For each step, data validation ensures the adequacy of the data to build the model, to evaluate the model, to test the simulation model.

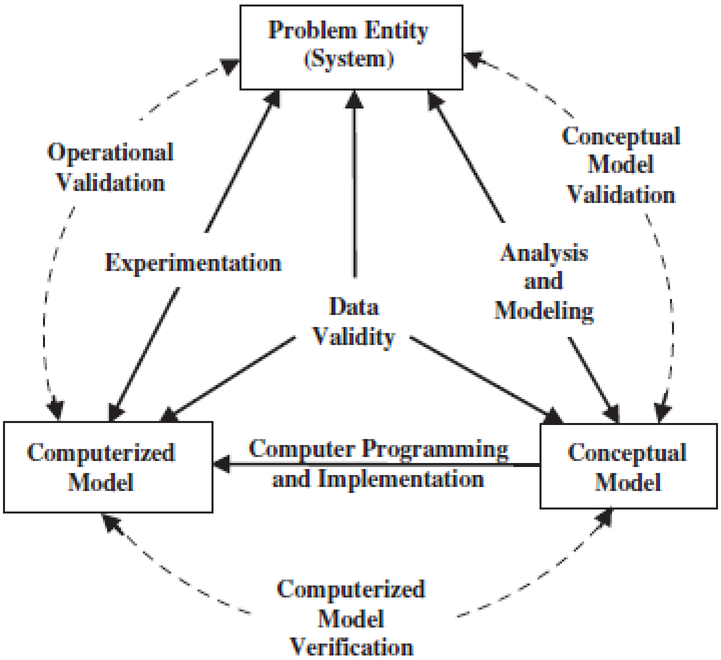

Figure 1. 13 : Verification and validation processes according to Sargent (2013).

Data validation

Data plays an important role in the construction and the validation of the simulation model. Data helps to identify the theories and relationships observed in the real world and in developing the formalisms and mathematical algorithms describing them. The use of assumptions and parameter estimations are also based on these data. The data also helps to validate the model during the operational validation phase by comparing the observed trends to the model outputs (Arlot and Celisse 2010).

Therefore it is important to properly collect and organize them in a database (Law 2008). Relationships between variables should be maintained when the variables are not directly those collected in the field. Outliners or extreme values should also be considered in order to understand if there is potentially an erroneous value or extreme behaviors

However, it is difficult to obtain appropriate and conclusive data. NAMASTE was developed based on data from farmer surveys (27 surveys oriented on technical practices and 684 surveys on farm characteristics) and surveys of the village heads and input sellers. It also used experimental plots data, meteorological data and market prices from the watershed or the state (Karnataka). Despite the large number of data source, these data were not always sufficient to the model development and its validation. The most critical data in our approach are those related to crops. Only five crops from over twenty were followed in experimental plots, no data on crop rotation, crop sequences and crop precedence effects were obtained for two main reasons: 1) the technical practices are not archived, and the literature review is very limited; 2) Indian farmers are not familiar with these agronomic concepts. In addition to a quantitatively limited calibration, data on system behavior are not available because of the archiving problem of the technical activities and crop choices made from one year to another. This limitation reconsiders the reliability of the model and its calibration. Today NAMASTE is considered qualitatively acceptable but will need further calibration and assessments to be considered quantitatively representative.

Conceptual validation

Conceptual validation is essential to ensure that the assumptions, theories and simplifications used to build the conceptual model are sufficiently accurate and relevant to meet the stakeholders' requirements and the objectives of the study (Costal et al. 1996; Borenstein 1998; Liu et al. 2011). To validate the conceptual model, we used: i) face validation that consists in asking experts and knowledgeable individuals about the study objectives to evaluate the conceptual model and determine whether it is correct and reasonable for the study purpose; and ii) traces techniques that consists in tracking entities through each sub-model and the overall model to determine whether the model's logic and the necessary accuracy are maintained (Robinson 2010; Sargent 2010; Robinson 2014). Conceptual validation is inherently an informal process referring to subjective and human judgement.

Each sub-model and the overall model must be evaluated to determine if they are reasonable and correct. First, we applied White-Box validation to the sub-models to determine whether each constituent part of the conceptual model represents the real world with sufficient accuracy to meet the study objectives (Robinson 2014). Each sub-system was validated by experts in the associated research field. Both experts and modelers were essential to build the decision sub-model. Modelers ensure that decision processes are appropriately designed into the chosen framework and formalisms. Indian agronomic researchers validated the decision rules for crop management and adaption. We also asked Indian researchers from the research project to participate to the validation of each sub-model as main stakeholders on the project and to certify the representation and data used to build the external system.

Second, we applied Black-Box validation to the overall model to determine whether the model provide a sufficiently accurate representation of the real world for the intended purpose of the study (Robinson 2014). The entire system was validated by experts on the different sub-systems, modelers and the Indian researchers. They worked on the consistency between inputs and outputs of each sub-system to ensure rational interactions between systems. Specification of each sub-model was circulated among those who have a detailed knowledge of the system. They shared feedbacks on whether the model was relevant by determining if the appropriate details and aggregate relationships were used for the model's intended purpose.

Basically, the conceptual validation used in NAMASTE involves a subjective process based on informal intuitive human judgment. Conceptual validation is essential to reduce the risk of distortions and errors on further model development steps; however conceptual validation is not enough to the validation of the final production model. It must be supported by mathematical validation and statistical validation approaches during the next steps of model development.

Computer model verification

The verification of the computer model ensures that its implementation matches the expectations of the conceptual model. Simulation models are often large computer models that can be the subject of computer bugs or coding errors. The verification therefore ensures the absence of coding errors and verifies that the simulation language used has been properly implemented in computer programming (Borenstein 1998).

We used two basic approaches for the verification of NAMASTE: the static approach and the dynamic approach. The first approach leads to include anti-bugs and unitary tests all along the code that locally checks locally the program. The second one consists of running the program in different conditions and analyzes the outputs to ensure the proper behavior of the model and to reveal possible implementation errors.

However, we should consider that errors identified during the computer model verification may be due to the conceptual model itself, to the computer program with coding errors or non-optimization of the programming language or to the data used in the dynamic approach (Whitner and Balci 1986).

Operational validation

The operational validation determines whether the behavior of the final simulation model has the required accuracy to meet the expectations and primary research objectives (Kleijnen 1995). The operational validation uses the developed simulation model, which implies that any malfunction can come from what has been developed in the preceding steps of model development, as well as from the assumptions, the theories or the data (Refsgaard and Knudsen 1996).

The operational validation can be done objectively by comparing the behavior of the simulation model outputs to the observed system or other models with statistical tests or subjectively without statistical test (Sargent 2013).

The first objective validation approach uses hypothesis tests to compare means, variances and distributions between output variables and the observed system or other already validated models. The second objective validation approach uses confidence intervals based on means and standard deviations for each set of data obtained from system observations.

In NAMASTE, operational validation was mainly conducted subjectively. The first subjective validation approach uses graphical comparison between simulation results and observed system such as box plots, histograms and graphs that describe variables behavior. The second approach of subjective validation explores the simulation model behavior by analyzing the outputs of the simulation model. This exploration was done qualitatively by defining whether the directions and the magnitudes of the output variables are acceptable. Subjective validation may also be done quantitatively by precisely analyzing the directions and magnitudes of these variables. We used sensibility analyses to examine the behavior of the NAMASTE model.

1.5.4. A decision model for the AICHA project

Scaling up an agricultural production model

Upscaling from the farm level to catchment, regional and national level is a common approach in studying system behavior and dynamics such as farm adaptation to climate change (Gibbons et al. 2010), land use and land cover change to climate change (Rounsevell et al. 2014), ecosystem changes to biotic and abiotic processes (Nash et al. 2014). Peters et al. (2007) identified three domains of scales: 1) “fine” at the scale of an individual; 2) “intermediate” at the scale of groups of individuals and, 3) “broad” at the scale of large spatial extents such as landscape, region and the whole globe.

The appropriate scale is defined by the question or hypothesis of research and often requires the upscaling or downscaling of existing models (Gibbons et al. 2010). We consider the problem of upscaling from the perspective of modeling the retro-action of farmers’ adaptation to climatic change and groundwater evolution. We emphasize upscaling from the farm level to the catchment level. The underlying scale is the farm level where farmers' decision making occurs and resources are allocated. To study the global impact and retro-action of groundwater evolution and climate change on farmers' practices we upscale the farm model developed during this thesis.

Two main methods of upscaling can be used: 1) simple model replication of the farm models for each unit (farms) modeled; 2) model aggregation. The first approach is computationally intensive and requires sufficient data and knowledge of farmers' characteristics for the farm model specification and calibration (Rounsevell et al. 2014). We will use the aggregation approach by globally representing all individual farmers and classifying them according to a limited number of clearly defined decision-making strategies, following the typology proposed in Chapter 3.

The aggregation or upscaling challenge is to determine which fine-scale details actually matter at intermediate or broad scales. Research questions are different depending on the scale. At the farm scale, we focused on decision-making processes of farmers and their adaptation to uncertain changes (e.g. climate, resource availability). At the watershed scale the issue is to look at the effect of decision making on groundwater table rather than the process of decision making itself and to consider interactions between individuals for shared resources. At the watershed scale, relative trends become more important than absolute levels. For instance at the watershed level, we will be more interested in total catchment used of groundwater for irrigation rather than individual farm uses.

Toward the spatialization of the decision model at the watershed scale

Based on the typology established in Chapter 3, the three types of farms 1) large, diversified and productivist farms, 2) small and marginal rainfed farms, and 3) small, irrigated marketing farms, are spatialized on the watershed (Figure 1.6).

The required data for the calibration of the farm model are: the farm size, the number of plot, the number of available resources (owned by the farm and hired from the village), the number of hours of electricity available, the type of soil, the water table depth (Table 1.1).

Table 1.1 Summary of farm characteristics by farm type and village

	variables	V1	V2	V3	V4	V5
Type1	proportion	7%	4%	36%	15%	6%
	farm size (ha)	3	3	3	3	3
	# plots	4	4	4	4	4
	# male from household	2	2	2	2	2
	# female from household	1	1	1	1	1

	# tractor from household	0	0	0	0	0
	# bullock from household	1	1	1	1	1
Type2	proportion	1%	28%	44%	67%	92%
	farm size (ha)	1	1	1	1	1
	# plots	1	1	1	1	1
	# male from household	2	2	2	2	2
	# female from household	1	1	1	1	1
	# tractor from household	0	0	0	0	0
	# bullock from household	2	2	2	2	2
Type3	proportion	92%	68%	20%	18%	2%
	farm size (ha)	2	2	2	2	2
	# plots	2	2	2	2	2
	# male from household	2	2	2	2	2
	# female from household	1	1	1	1	1
	# tractor from household	0	0	0	0	0
	# bullock from household	2	2	2	2	2
Village	# labor male	2000	2000	870	1170	380
	# labor female	1800	1500	710	822	340
	# tractor	15	13	41	14	7
	# bullock	60	200	306	424	128
	hours of electricity kharif	3	3	4	4	4
	hours of electricity rabi	3	3	3	3	3
	soil type	Clay/sandy loam/loamy sand/ sandy clay loam	Sandy clay loam/clay/loamy sand/sandy loam/gravely loamy sand	Sandy clay loam/clay/loamy sand/sandy loam/gravely loamy sand	Clay loam/clay/sandy clay loam/sandy loam/gravely loamy sand	Sandy clay loam/gravely loamy sand/clay loam/clay/sandy loam
	groundwater level (m)	[46,60]	[36,45]	[26 ;35]	[7,15]	[16,25]

A total of 1352 farms were identified by the Bhoomi - Tahasildar Office (Gundlupet) in the village V1, 1052 farms in V2, 1545 farms in V3, 1041 farms in V4 and 471 farms in V5. Crossed to the characteristics of the farm types presented below, it corresponds to 2881 crop plots in V1, 1893 crop plots in V2, 3522 crop plots in V3, 1697 crop plots in V4 and 565 crop plots in V5.

The modeling of the groundwater in the basin Berambadi (84 km²) corresponds to 8400 AMBHAS cells of a hectare with different characteristics in terms of initial water table depth, porosity and transmissivity (lateral flow of water between cells). By spatializing farms on this AMBHAS grid cells, farms of type 1 are located on three AMBHAS cells, those of type 2 are on one AMBHAS cell and those of type 3 are on two AMBHAS cells.

At the watershed scale, we have to consider the borewell location when a farm is located on several AMBHAS cells in order to spatialize the village model developed in the thesis, Indeed, given the different characteristics of the AMBHAS cells, a well dug on a certain cell does not behave in the same manner as on the neighboring cell. The spatialized model will therefore need to maximize borewell locations on the farm. To do so, it will be necessary to integrate the characteristics of the different cells (initial water table height, table height variation equation) into the strategic decision model (Chapter 6) to optimize and locate the borewells on the AMBHAS cell. Interference between borewells will be taken into account when several borewells are drilled on the same AMBHAS cell. Indeed the discharge of two borewells is less than twice the discharge of one borewell (the flow rate of the borewell is affected by the pumping of other borewell on the same AMBHAS cell, which implies that the overall flow of the two borewells is less than twice the unitary rate).

Soil type also varies within the same village. Thus, each cell of one hectare should be associated with a specific soil type (Figure 1.14).

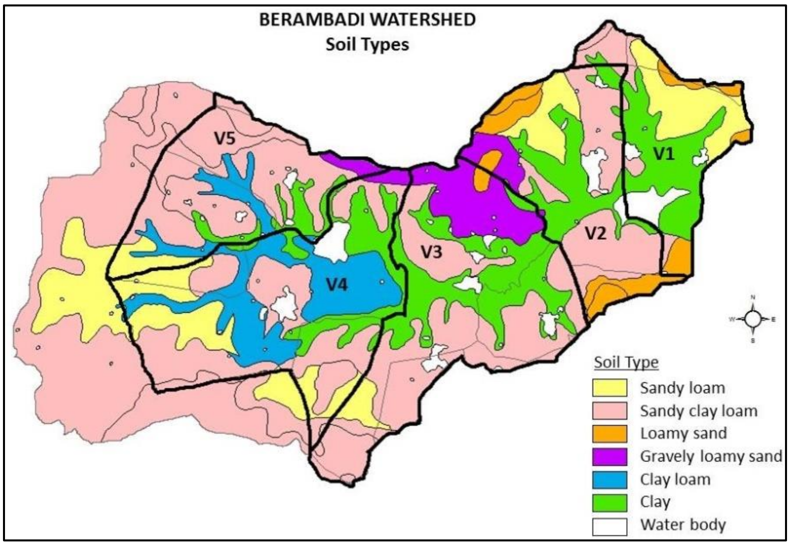

Figure 1.14 : Soil map over the Berambadi watershed showing the intra- and inter-village heterogeneity.

From a modeling perspective, spatialization on the watershed involves as many strategic and tactical models as farms to be represented (5461 farms), five models of operational decisions for the management of resources (one per village), as many STICS crop model as plots which represents 10558 STICS models.

A West-East weather gradient is also observed in the catchment area from a humid climate at the west (data from the Maddur weather station) to a semi-humid climate at the east (data from the Kannegala weather station). The modeling of the watershed should consider this climate gradient.

To run these simulations we should use a 200 GB RAM for a running time of 24 to 72 hours for 626 days of simulation.

This long simulation time could be an issue for the rest of the project. Approaches aiming at decreasing the simulation time can be considered: 1) change the grid resolution of the watershed, 2) reduce the study area by dividing the watershed into subzones. The first approach makes important assumptions on the homogeneity of soil consistency, behavior of the groundwater table and climate on each grid cell. The second approach implies ignoring the exchange between sub-basins in terms of lateral flow and assumes that subzones are independent.

Scenarios at the watershed scale

In order to design tools for effective management of groundwater (limiting depletion and pollution of the groundwater resource) and of innovative, robust and resilient agricultural production systems, the scenarization on the watershed will be based on a participatory design process involving both agricultural stakeholders and decision makers or farm advisors (Leenhardt et al. 2015; Murgue et al. 2015). This approach engages a social learning process that will allow the negotiation of satisfactory solutions rather than optimized solutions for a single purpose (Giampetro 2002; Pahl-Wostl and Hare 2004; Newig et al. 2008; Sterk et al. 2009). The challenge will be to get participants to express as clearly as possible their views on possible changes at the catchment scale in order to identify the concepts and objectives for evaluation. This evaluation of scenarios will be made by running the simulation model for each proposed scenario. It will allow seeing the effects of these possible changes on the quantitative and qualitative evolution of groundwater on the Berambadi watershed.

Possible scenarii based on my thesis work are:

- Climate change scenario: a report published by the Bangalore Climate Change Initiative - Karnataka (BCCI-K) in 2011 predicts a decline of 1.85% of annual rainfall and a rise of 1.96°C in average temperatures associated with higher drought frequency in the district Chamaraja Najar between 2021 and 2050.
- Crop subsidies: rainfed cropping systems may be encouraged by the establishment of subsidies to cover the risks incurred without the support of irrigation. Crops such as pulses (lentils, chickpeas) which are the basis of Indian food have been neglected these last years in favor of more lucrative cash crops. Between 2015 and 2016, India imported 5.8 million tonnes of pulses mainly produced in Africa. Subsidies encouraging local production of pulses can also be considered.
- Piezometric taxation: this global tax evolving with the decline of the groundwater table, impacts all irrigating farmers on the same water table regardless of pumping intensity. It can be a good policy to limit groundwater extraction.
- Electricity management: even if the access to electricity is limited to few hours per day on the watershed, free electricity does not limit over-consumption behaviors. Charging electricity could makes farmers aware of resource depletion.
- Irrigation quota: quotas are a fairly common practice in water management policies (Graveline 2013), however they require that each borewell / pump is equipped with a water meter.

- Collecting rainfall for irrigation: the use of water retention basin (ponds) is an ancient technique in the watershed that was abandoned in favor of individual pumping. Subsidies for the establishment or upgrading of the status of individual or collective ponds can encourage the collection and use of rainwater for irrigation.
- Collection of rainfall water for direct recharge of the aquifer: collected rainfall water (runoff from roofs, retention pond) could be conducted to the old open wells for the direct recharge of the aquifer.

1.6. CONCLUSION

The objectives of this thesis were to represent farmers' decision-making and adaptation processes, and conceive a flexible and resilient agricultural production system under a context of water scarcity and climate change.

We provided a necessary, original, and useful step-by-step methodology that guides data acquisition and analysis, incorporation of farmers' knowledge, and model design.

We identified three main ideas in the scientific literature that are interesting to consider when modeling a farming system: i) a systemic representation is relevant, ii) dynamic processes bring the farming system to life (Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Aubry et al. 1998a; Osman 2010), (Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010)(Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010)(Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010)and iii) farmers' decision-making processes are flexible and adaptive over time and space (Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014)(Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014)(Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014)(Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014). We developed an original representation of farming systems that integrates these aspects into a new conceptual model.

NAMASTE simulates the decisions of farmers in different time (strategic, tactical, operational) and space (from the farm to the plot) scales. It represents the interactions between farmers for resource uses such as water, labor and equipment. The model also emphasizes the feedback and retroaction between farming practices and changes in the water table (e.g. pumping impact on groundwater availability, water availability impact on farming practices).

The model was initially developed to address critical issues of groundwater depletion and farming practices in a watershed in southwestern India. Its structure, frameworks and formalisms can be used in other agricultural contexts. Our application focused on water management in semi-arid agricultural systems, but it can also be applied to other farming systems to confirm the re-usability and applicability of the framework.

For the AICHA project, we proposed a farm model that will be useful for future upscaling at the watershed scale.

Chapter 2

Processes of adaptation in farm decision-making models- A review

Marion Robert[1,*], Alban Thomas[2], Jacques-Eric Bergez[1]

[1] INRA, Université Fédérale de Toulouse, UMR 1248 AGIR, F-31326 Castanet-Tolosan, France

[2] Toulouse School of Economics, INRA, University of Toulouse, F-31000 Toulouse, France

*: Corresponding author, Tel: +33 (0)5 61 28 50 30. E-mail: marion.robert@inra.fr

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Agricultural production systems should evolve fast to cope with risks induced by climate change. Farmers should adapt their management strategies to stay competitive and satisfy the societal demand for sustainable food systems. It is therefore important to understand decision-making processes used by farmers for adaptation. Processes of adaptation are in particular addressed by bio-economic and bio-decision models.

Here we review bio-economic and bio-decision models, in which strategic and tactical decisions are included in dynamic adaptive and expectation-based processes, in 40 literature articles. The major points are: adaptability, flexibility and dynamic processes are common ways to characterize farmers' decision-making. Adaptation is either a reactive or a proactive process depending on farmer flexibility and expectation capabilities. Various modeling methods are used to model decision stages in time and space, and some methods can be combined to represent a sequential decision-making process.

Keywords: farmers' decision-making, bio-economic model, bio-decision model, uncertainty, adaptation

2.1. INTRODUCTION

Agricultural production systems are facing new challenges due to a constantly changing global environment that is a source of risk and uncertainty, and in which past experience is not sufficient to gauge the odds of a future negative event. Concerning risk, farmers are exposed to production risk mostly due to climate and pest conditions, to market risk that impact input and output prices, and institutional risk through agricultural, environmental and sanitary regulations (Hardaker 2004). Farmers may also face uncertainty due to rare events affecting, e.g. labor, production capital stock, and extreme climatic conditions, which add difficulties to producing agricultural goods and calls for re-evaluating current production practices. To remain competitive, farmers have no choice but to adapt and adjust their daily management practices (Hémidy et al. 1996; Hardaker 2004; Darnhofer et al. 2010; Dury 2011) (Figure 2.1). In the early 1980s, Petit developed the theory of the "farmer's adaptive behavior" and claimed that farmers have a permanent capacity for adaptation (Petit 1978). Adaptation refers to adjustments in agricultural systems in response to actual or expected stimuli through changes in practices, processes and structures and their effects or impacts on moderating potential modifications and benefiting from new opportunities (Grothmann and Patt 2003; Smit and Wandel 2006). Another important concept in the scientific literature on adaptation is the concept of adaptive capacity or capability (Darnhofer 2014). This refers to the capacity of the system to resist evolving hazards and stresses (Ingrand et al. 2009; Dedieu and Ingrand 2010) and it is the degree to which the system can adjust its practices, processes and structures to moderate or offset damages created by a given change in its environment (Brooks and Adger 2005; Martin 2015). For authors in the early 1980s such as Petit (1978) and Lev and Campbell (1987), adaptation is seen as the capacity to challenge a set of systematic and permanent disturbances. Moreover, agents integrate long-term considerations when dealing with short term changes in production. Both claims lead to the notion of a permanent need to keep adaptation capability under uncertainty. Holling (2001) proposed a general framework to represent the dynamics of a socio-ecological system based on both ideas above, in which dynamics are represented as a sequence of "adaptive cycles", each affected by disturbances. Depending on whether the latter are moderate or not, farmers may have to reconfigure the system, but if such redesigning fails, then the production system collapses.

Some of the most common dimensions in adaptation research on individual behavior refer to the timing and the temporal and spatial scopes of adaptation (Smit et al. 1999; Grothmann and Patt 2003). The first dimension distinguishes proactive vs. reactive adaptation. Proactive adaptation refers to anticipated adjustment, which is the capacity to anticipate a shock (change that can disturb farmers' decision-making processes); it is also called anticipatory or ex-ante adaptation. Reactive adaptation is associate with adaptation performed after a shock; it is also called responsive or ex-post adaptation (Attonaty et al. 1999; Brooks and Adger 2005; Smit and Wandel 2006). The temporal scope distinguishes strategic adaptations from tactical adaptations, the former referring to the capacity to adapt in the long term (years), while the latter are mainly instantaneous short-term adjustments (seasonal to daily) (Risbey et al. 1999; Le Gal et al. 2011). The spatial scope of adaptation opposes localized adaptation versus widespread adaptation. In a farm production context, localized adaptations are often at the plot scale, while widespread adaptation concerns the entire farm. Temporal and spatial scopes of adaptation are easily considered in farmers' decision-making processes; however, incorporating the timing scope of farmers' adaptive behavior is a growing challenge when designing farming systems.

System modeling and simulation are interesting approaches to designing farming systems which allow limiting the time and cost constraints (Rossing et al. 1997; Romera et al. 2004; Bergez et al. 2010) encountered in other approaches, such as diagnosis (Doré et al. 1997), systemic experimentation (Mueller et al. 2002) and prototyping (Vereijken 1997). Modeling adaptation to uncertainty when representing farmers' practices and decision-making processes has been addressed in bio-economic and bio-decision approaches (or management models) and addressed at different temporal and spatial scales.

The aim of this paper is to review the way adaptive behaviors in farming systems has been considered (modeled) in bio-economic and bio-decision approaches. This work reviews several modeling formalisms that have been used in bio-economic and bio-decision approaches, comparing their features and selected relevant applications. We chose to focus on the formalisms rather than the tools as they are the essence of the modeling approach.

Approximately 40 scientific references on this topic were found in the agricultural economics and agronomy literature. This paper reviews approaches used to model farmers' adaptive behaviors when they encounter uncertainty in specific stages of, or throughout, the decision-making process. There is a vast literature on technology adoption in agriculture, which can be considered a form of adaptation, but which we do not consider here, to focus on farmer decisions for a given production technology. After presenting some background on modeling decisions in agricultural economics and agronomy and the methodology used, we present formalisms describing proactive behavior and anticipation decision-making processes and formalisms for representing reactive adaptation decision-making processes. Then we illustrate the use of such formalisms in papers on modeling farmers' decision-making processes in farming systems. Finally, we discuss the need to include adaptation and anticipation to uncertain events in modeling approaches of the decision-making process and discuss adaptive processes in other domains.

2.2. Background on modeling decisions in agricultural economics and agronomy

Two main fields dominate decision-making approaches in farm management: agricultural economics (with bio-economic models) and agronomy (with bio-decision models) (Pearson et al. 2011). Agricultural economists are typically interested in the analysis of year-to-year strategical (sometimes tactical) decisions originating from long-term strategies (e.g., investment and technical orientation). In contrast, agronomists focus more on day-to-day farm management described in tactical decisions. The differences in temporal scale are due to the specific objective of each approach. For economists, the objective is to efficiently use scarce resources by optimizing the configuration and allocation of farm resources given farmers' objectives and constraints in a certain production context. For agronomists, it is to organize farm practices to ensure farm production from a biophysical context (Martin et al. 2013). Agronomists identify relevant activities for a given production objective, their interdependency, what preconditions are needed to execute them and how they should be organized in time and space. Both bio-economic and bio-decision models represent farmers' adaptive behavior.

Bio-economic models integrate both biophysical and economic components (Knowler 2002; Flichman 2011). In this approach, equations describing a farmer's resource-management decisions are combined with those representing inputs to and outputs from agricultural activities (Janssen and van Ittersum 2007). The main goal of farm-resource allocation in time and space is to improve economic performance of farming systems, usually along with environmental performance. Bio-economic models indicate the optimal management behavior to adopt by describing agricultural activities. Agricultural activities are characterized by an enterprise and a production technology used to manage the activity. Technical coefficients represent relations between inputs and outputs by stating the amount of inputs needed to achieve a certain amount of outputs (e.g., matrix of input-output coefficients, see Janssen and van Ittersum 2007). Many farm-management decisions can be formulated as a multistage decision-making process in which farmer decision-making is characterized by a sequence of decisions made to meet farmer objectives. The time periods that divide the decision-making process are called stages and represent the moments when decisions must be made. Decision making is thus represented as a dynamic and sustained process in time (Bellman 1954; Mjelde 1986; Osman 2010). This means that at each stage, technical coefficients are updated to proceed to the next round of optimization. Three major mathematical programming techniques are commonly used to analyze and solve models of decision under uncertainty: recursive models, dynamic stochastic programming, and dynamic programming (see Miranda and Fackler 2004). Agricultural economic approaches usually assume an idealized situation for decision, in which the farmer has clearly expressed goals from the beginning and knows all the relevant alternatives and their consequences. Since the farmer's rationality is considered to be complete, it is feasible to use the paradigm of utility maximization (Chavas et al. 2010). Simon (1950) criticized this assumption of full rationality and claimed that decision-makers do not look for the best decision but for a satisfying one given the amount of information available. This gave rise to the concept of bounded and adaptive rationality (Simon 1950; Cyert and March 1963), in which the rationality of decision-makers is limited by the information available, cognitive limitations of their minds and the finite timing of the decision. In bounded rationality, farmers tend to look for satisfactory rather than utility maximization when making relevant decisions (Kulik and Baker, 2008). From complete or bounded rationality, all bio-economic approaches are characterized by the common feature of computing a certain utility value for available options and then selecting the one with the best or satisfactory value. In applied agricultural economics, stochastic production models are more and more commonly used to represent the sequential production decisions by farmers, by specifying the production technology through a series of operational steps involving production inputs. These inputs have often the dual purpose of controlling crop yield or cattle output level on the one hand, and controlling production risk on the other (Burt 1993; Maatman et al. 2002; Ritten et al. 2010). Furthermore, sequential production decisions with risk and uncertainty can also be specified in a dynamic framework, to account for intertemporal substitutability between inputs (Fafchamps 1993). Dynamic programming models have been used as guidance tools in policy analysis and to help farmers identify irrigation strategies (Bryant et al. 1993).

Biophysical models have been investigated since the 1970s, but the difficulty in transferring simulation results to farmers and extension agents led researchers to investigate farmers' management practices closely and develop bio-decision models (Bergez et al. 2010). A decision model, also known as a decision-making process model or farm-management model, comes from on-farm observations and extensive studies of farmers' management practices. These studies, which show that farmers' technical decisions are planned, led to the "model for action" concept (Matthews et al. 2002), in which decision-making processes are represented as a sequence of technical acts. Rules that describe these technical acts are organized in a decision schedule that considers sequential, iterative and adaptive processes of decisions (Aubry et al. 1998). In the 1990s, combined approaches represented farming systems as bio-decision models that link the biophysical component to a decisional component based on a set of decision rules (Aubry et al. 1998b; Attonaty et al. 1999; Bergez et al. 2006; Bergez et al. 2010). Bio-decision models describe the appropriate farm-management practice to adopt as a set of decision rules that drives the farmer's actions over time (e.g., a vector returning a value for each time step of the simulation). Bio-decision models are designed (proactive) adaptations to possible but anticipated changes. By reviewing the decision rules, these models also describe the farmer's reactive behavior.

2.3. METHOD

To achieve the above goal, a collection of articles was assembled through three steps. The first step was a search on Google Scholar using the following combination of keywords: Topic = ((decision-making processes) or (decision model) or (knowledge-based model) or (object-oriented model) or (operational model)) AND Topic = ((bio-economics or agricultural economics) or (agronomy or bio-decision)) AND Topic = ((adaptation) or (uncertainty) or (risk)). The first topic defines the tool of interest: only work using decision-making modeling (as this is the focus of this paper). Given that different authors use slightly different phrasings, the present paper incorporated the most-commonly used alternative terms such as knowledge-based model, object-oriented model, and operational model. The second topic restricts the search to be within the domains of bio-economics and agronomy. The third topic reflects the major interest of this paper, which relates to farmer adaptations facing uncertain events. This paper did not use "AND" to connect the parts within topics because this is too restrictive and many relevant papers are filtered out.

The second step was a classification of formalisms referring to the timing scopes of the adaptation. We retained the timing dimension as the main criteria for the results description in our paper. The timing dimension is an interesting aspect of adaptation to consider when modeling adaptation in farmers' decision-making processes. Proactive processes concern the ability to anticipate future and external shocks affecting farming outcomes and to plan corresponding adjustments. In this case, adaptations processes are time-invariant and formalisms describing static processes are the most appropriate since they describe processes that do not depend explicitly on time. Reactive processes describe the farmer's capacity to react to a shock. In this case, adaptation concerns the ability to update the representation of a shock and perform adaptations without any anticipation. In this case adaptation processes are time-dependent and formalisms describing dynamic processes are the most appropriate since they describe processes that depend explicitly on time (Figure 2.2). Section 4 presents these results.

The third step was a classification of articles related to farm management in agricultural economics and agronomy referring to the temporal and spatial scopes of the adaptation. This last step aimed at illustrating the use of the different formalisms presented in the fourth section to model adaptation within farmer decision-making processes. This section is not supposed to be exhaustive but to provide examples of use in farming system literature. Section 5 presents these results.

2.4. FORMALISMS TO MANAGE ADAPTIVE DECISION-MAKING PROCESSES

This section aims at listing formalisms used to manage adaptive decision-making processes in both bio-economic and bio-decision models. Various formalisms are available to describe adaptive decision-making processes. Adaptation processes can be time-invariant when it is planned beforehand with a decision tree, alternative and optional paths and relaxed constraints to decision processes. Adaptation processes can be time-varying when it is reactive to a shock with dynamic internal changes of the decision process via recursive decision, sequential decision or reviewed rules. We distinguish proactive or anticipated processes to reactive processes. Six formalisms were included in this review.

2.4.1. Formalisms in proactive adaptation processes

In proactive or anticipated decision processes, adaptation consists in the iterative interpretation of a flexible plan built beforehand. The flexibility of this anticipatory specification that allows for adaptation is obtained by the ability to use alternative paths, optional paths or by relaxing constraints that condition a decision.

Anticipated shocks in sequential decision-making processes

When decision-making process is assumed to be a succession of decisions to make, it follows that farmers are able to integrate new information about the environment at each stage and adapt to possible changes occurring between two stages. Farmers are able to anticipate all possible states of the shock (change) to which they will have to react. In 1968, Cocks stated that discrete stochastic programming (DSP) could provide solutions to sequential decision problems (Cocks 1968). DSP processes sequential decision-making problems in discrete time within a finite time horizon in which knowledge about random events changes over time (Rae 1971; Apland and Hauer 1993). During each stage, decisions are made to address risks. One refers to “embedded risk” when decisions can be divided between those initially made and those made at a later stage, once an uncertain event has occurred (Trebeck and Hardaker 1972; Hardaker 2004). The sequential and stochastic framework of the DSP can be represented as a decision tree in which nodes describe the decision stages and branches describe anticipated shocks. Considering two stages of decision, the decision-maker makes an initial decision (u_1) with uncertain knowledge of the future. After one of the states of nature of the uncertain event occurs (k), the decision-maker will adjust by making another decision (u_{2k}) in the second stage, which depends on the initial decision and the state of nature k of the event. Models can become extremely large when numerous states of nature are considered; this “curse of dimensionality” is the main limitation of these models (Trebeck and Hardaker 1972; Hardaker 2004).

Flexible plan with optional paths and interchangeable activities

In manufacturing, proactive scheduling is well-suited to build protection against uncertain events into a baseline schedule (Herroelen and Leus 2004; Darnhofer and Bellon 2008). Alternative paths are considered and choices are made at the operational level while executing the plan. This type of structure has been used in agriculture as well, with flexible plans that enable decision-makers to anticipate shocks. Considering possible shocks that may occur, substitutable components, interchangeable partial plans, and optional executions are identified and introduced into the nominal plan. Depending on the context, a decision is made to perform an optional activity or to select an alternative activity or partial plan (Clouaire and Rellier 2009). Thus, two different sequences of events would most likely lead to performing two different plans. Some activities may be cancelled in one case but not in the other depending on whether they are optional or subject to a context-dependent choice (Bralts et al. 1993; Castellazzi et al. 2008; Dury et al. 2010; Castellazzi et al. 2010).

Relaxed constraints on executing activities

Management operations on biophysical entities are characterized by a timing of actions depending on their current states. The concept of bounded rationality, presented earlier, highlights the need to obtain satisfactory results instead of optimal ones. Following the same idea, Kemp and Michalk (2007)point out that "farmers can manage more successfully over a range than continually chasing optimum or maximum values". In practice, one can easily identify an ideal time window in which to execute an activity that is preferable or desirable based on production objectives instead of setting a specific execution date in advance (Shaffer and Brodahl 1998b; Aubry et al. 1998b; Taillandier et al. 2012b). Timing flexibility helps in managing uncontrollable factors.

2.4.2. Formalisms in reactive adaptation processes

In reactive decision processes, adaptation consists in the ability to perform decisions without any anticipation by integrating gradually new information. Reactivity is obtained by multi-stage and sequential decision processes and the integration of new information or the set-up of unanticipated path within forehand plan.

Gradual adaptation in a repeated process

The recursive method was originally developed by Day (1961) to describe gradual adaptation to changes in exogenous parameters after observing an adjustment between a real situation and an optimal situation obtained after optimization (Blanco-Fonseca et al. 2011). Recursive models explicitly represent multiple decision stages and optimize each one; the outcome of stage n is used to reinitialize the parameters of stage $n+1$. These models consist of a sequence of mathematical programming problems in which each sub-problem depends on the results of the previous sub-problems (Day 1961; Day 2005; Janssen and van Ittersum 2007; Blanco-Fonseca et al. 2011). In each sub-problem, dynamic variables are re-initialized and take the optimal values obtained in the previous sub-problem. Exogenous changes (e.g., rainfall, market prices) are updated at each optimization step. For instance, the endogenous feedback mechanism for a resource (e.g., production input or natural resource) between sub-periods is represented with a first-order linear difference equation: R_t = A_{t-1}GX^*_{t-1} + YR_{t-1} + C_t,where the resource level of period t (R_t) depends on the optimal decisions (X^*_{t-1}) and resource level at t-1 (R_{t-1}) and on exogenous variables (C_t). The Bayesian approach is the most natural one for updating parameters in a dynamic system, given incoming period-dependent information. Starting with an initial prior probability for the statistical distribution of model parameters, sample information is used to update the latter in an efficient and fairly general way (Stengel 1986). The Bayesian approach to learning in dynamic systems is a special but important case of *closed-loop* models, in which a feedback loop regulates the system as follows: depending on the (intermediate) observed state of the system, the control variable (the input) is automatically adjusted to provide path correction as a function of model performance in the previous period.

Adaptation in sequential decision-making processes

In the 1950s, Bellman presented the theory of dynamic programming (DP) to emphasize the sequential decision-making approach. Within a given stage, the decision-making process is characterized by a specific status corresponding to the values of state variables. In general, this method aims to transform a complex problem into a sequence of simpler problems whose solutions are optimal and lead to an optimal solution of the initial complex model. It is based on the principle of optimality, in which "an optimal policy has the property that whatever the initial state and decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decisions" (Bellman 1954). DP explicitly considers that a decision made in one stage may affect the state of the decision-making process in all subsequent stages. State-transition equations are necessary to link the current stage to its successive or previous stage, depending on whether one uses a forward or backward DP approach, respectively. In the Bellman assumptions (backward DP), recursion occurs from the future to the present, and the past is considered only for the initial condition. In forward DP, stage numbering is consistent with real time. The optimization problem defined at each stage can result in the application of a wide variety of techniques, such as linear programming (Yaron and Dinar 1982) and parametric linear programming (Stoecker et al. 1985). Stochastic DP is a direct extension of the framework described above, and efficient numerical techniques are now available to solve such models, even though the curse of dimensionality may remain an issue (Miranda and Fackler 2004).

Reactive plan with revised and new decision rules

An alternative to optimization is to represent decision-making processes as a sequence of technical operation organized through a set of decision rules. This plan is reactive when rules are revised or newly introduced after a shock. Revision is possible with simulation-based optimization, in which the rule structure is known and the algorithm looks for optimal indicator values or thresholds. It generates a new set of indicator thresholds to test at each new simulation loop (Nguyen et al. 2014). For small discrete domains, the complete enumeration method can be used, whereas when the optimization domain is very large and a complete enumeration search is no longer possible, heuristic search methods are considered, such as local searching and branching methods. Search methods start from a candidate solution and randomly move to a neighboring solution by applying local changes until a solution considered as optimal is found or a time limit has passed. Metaheuristic searches using genetic algorithms, Tabu searches and simulated annealing algorithms are commonly used (Nguyen et al. 2014). Control-based optimization is used to add new rules to the plan. In this case, the rule structure is unknown, and the algorithm optimizes the rule's structure and optimal indicator values or thresholds. Crop-management decisions can be modeled as a Markov control problem when the distribution of variable X_{i+1} depends only on the current state X_i and on decision D_i that was applied at stage i. The decision-making process is divided into a sequence of N decision stages. It is defined by a set of possible states s, a set of possible decisions d, probabilities describing the transitions between successive states and an objective function (sum of expected returns) to be maximized. In a Markov control problem, a trajectory is defined as the result of choosing an initial state s and applying a decision d for each subsequent state. The DSP and DP methods provide optimal solutions for Markov control problems. Control-based optimization and metaheuristic searches are used when the optimization domain is very large and a complete enumeration search is no longer possible.

2.5. Modeling adaptive decision-making processes in farming systems

This section aims at illustrating the use of formalisms to manage adaptive decision-making processes in farming systems both in bio-economic and bio-decision models. Around 40 papers using the six formalisms on adaptation have been found. We distinguish strategic adaptation at the farm level, tactic adaptation at the farm and plot scale and strategic and tactic adaptation both at the farm and plot scale.

2.5.1. Adaptations and strategic decisions for the entire farm

Strategic decisions aim to build a long-term plan to achieve farmer production goals depending on available resources and farm structure. For instance, this plan can be represented in a model by a cropping plan that selects the crops grown on the entire farm, their surface area and their allocation within the farmland. It also offers long-term production organization, such as considering equipment acquisition and crop rotations. In the long-term, uncertain events such market price changes, climate events and sudden resource restrictions are difficult to predict, and farmers must be reactive and adapt their strategic plans.

Barbier and Bergeron (1999) used the recursive process to address price uncertainty in crop and animal production systems; the selling strategy for the herd and cropping pattern were adapted each year to deal with price uncertainty and policy intervention over 20 years. Similarly, Heidhues (1966) used a recursive approach to study the adaptation of investment and sales decisions to changes in crop prices due to policy measures. Domptail and Nuppenau (2010) adjusted in a recursive process herd size and the purchase of supplemental fodder once a year depending on the available biomass that depended directly on rainfall. In a study of a dairy-beef-sheep farm in Northern Ireland, Wallace and Moss (2002) examined the effect of possible breakdowns due to bovine spongiform encephalopathy on animal-sale and machinery-investment decisions over a seven-year period with linear programming and a recursive process.

Thus, in the operation research literature, adaptation of a strategic decision is considered a dynamic process that should be modeled via a formalism describing a reactive adaptation processes (Table 2.1).

2.5.2. Adaptation and tactic decisions

Adaptation for the agricultural season and the farm

At the seasonal scale, adaptations can include reviewing and adapting the farm's selling and buying strategy, changing management techniques, reviewing the crop varieties grown to adapt the cropping system and deciding the best response to changes and new information obtained about the production context at the strategic level, such as climate (Table 2.1).

DSP was used to describe farmers' anticipation and planning of sequential decision stages to adapt to an embedded risk such as rainfall. In a cattle farm decision-making model, Trebeck and Hardaker (1972) represented adjustment in feed, herd size and selling strategy in response to rainfall that impacted pasture production according to a discrete distribution with "good", "medium", or "poor" outcomes. After deciding about land allocation, rotation sequence, livestock structure and feed source, Kingwell et al. (1993) considered that wheat-sheep farmers in western Australia have two stages of adjustment to rainfall in spring and summer: reorganizing grazing practices and adjusting animal feed rations. In a two-stage model, Jacquet and Pluvinage (1997) adjusted the fodder or grazing of the herd and quantities of products sold in the summer depending on the rainfall observed in the spring; they also considered reviewing crop purposes and the use of crops as grain to satisfy animal-feed requirements. Ritten et al. (2010) used a dynamic stochastic programming approach to analyze optimal stocking rates facing climate uncertainty for a stocker operation in central Wyoming. The focus was on profit maximization decisions on stocking rate based on an extended approach of predator-prey relationship under climate change scenarios. The results suggested that producers can improve financial returns by adapting their stocking decisions with updated expectations on standing forage and precipitation. Burt (1993) used dynamic stochastic programming to derive sequential decisions on feed rations in function of animal weight and accommodate seasonal price variation; he also considered decision on selling animals by reviewing the critical weight at which to sell a batch of animals. In the model developed by Adesina (1991), initial cropping patterns are chosen to maximize farmer profit. After observing low or adequate rainfall, farmers can make adjustment decisions about whether to continue crops planted in the first stage, to plant more crops, or to apply fertilizer. After harvesting, farmers follow risk-management strategies to manage crop yields to fulfill household consumption and income objectives. They may purchase grain or sell livestock to obtain more income and cover household needs. To minimize deficits in various nutrients in an African household, Maatman et al. (2002) built a model in which decisions about late sowing and weeding intensity are decided after observing a second rainfall in the cropping season.

Adaptation of the cropping system was also described using flexible plans for crop rotations. Crops were identified to enable farmers to adapt to certain conditions. Multiple mathematical approaches were used to model flexible crop rotations: Detlefsen and Jensen (2007) used a network flow, Castellazzi et al. (2008) regarded a rotation as a Markov chain represented by a stochastic matrix, and Dury (2011) used a weighted constraint-satisfaction-problem formalism to combine both spatial and temporal aspects of crop allocation.

Adaptation of daily activities at the plot scale

Daily adaptations concern crop operations that depend on resource availability, rainfall events and task priority. An operation can be cancelled, delayed, replaced by another or added depending on the farming circumstances (Table 2.1).

Flexible plans with optional paths and interchangeable activities are commonly used to describe the proactive behavior farmers employ to manage adaptation at a daily scale. This flexibility strategy was used to model the adaptive management of intercropping in vineyards (Ripoche et al. 2011); grassland-based beef systems (Martin et al. 2011b); and whole-farm modeling of a dairy, pig and crop farm (Chardon et al. 2012). For instance, in a grassland-based beef system, the beef production level that was initially considered in the farm management objectives might be reviewed in case of drought, and decided a voluntary underfeeding of the cattle (Martin et al. 2011b). McKinion et al. (1989) applied optimization techniques to analyze previous runs and hypothesize potentially superior schedules for irrigation decision on cotton crop. Rodriguez et al. (2011) defined plasticity in farm management as the results of flexible and opportunistic management rules operating in a highly variable environment. The model examines all paths and selects the highest ranking path.

Daily adaptations were also represented with timing flexibility to help manage uncontrollable factors. For instance, the cutting operation in the haymaking process is monitored by a time window, and opening predicates such as minimum harvestable yield and a specific physiological stage ensure a balance between harvest quality and quantity (Martin et al. 2011a). The beginning of grazing activity depends on a time range and activation rules that ensure a certain level of biomass availability (Cros et al. 1999). Shaffer and Brodahl (1998) structured planting and pesticide application event time windows as the outer-most constraint for this event for corn and wheat. Crespo et al. (2011) used time-window to insert some flexibility to the sowing of southern African maize.

2.5.3. Sequential adaptation of strategic and tactical decisions

Some authors combined strategic and tactical decisions to consider the entire decision-making process and adaptation of farmers (Table 2.1). DP is a dynamic model that allows this combination of temporal decision scales within the formalism itself: strategic decisions are adapted according to adaptations made to tactical decisions. DP has been used to address strategic investment decisions. Addressing climate uncertainty, Reynaud (2009) used DP to adapt yearly decisions about investment in irrigation equipment and selection of the cropping system to maximize farmers' profit. The DP model considered several tactical irrigation strategies, in which 12 intra-year decision points represented the possible water supply. To maximize annual farm profits in the face of uncertainty in groundwater supply in Texas, Stoecker et al. (1985) used results of a parametric linear programming approach as input to a backward DP to adapt decisions about investment in irrigation systems. Duffy and Taylor (1993) ran DP over 20 years (with 20 decision stages) to decide which options for farm program participation should be chosen each year to address fluctuations in soybean and maize prices and select soybean and corn areas each season while also maximizing profit.

DP was also used to address tactic decisions about cropping systems. Weather uncertainty may also disturb decisions about specific crop operations, such as fertilization after selecting the cropping system. Hyytiäinen et al. (2011) used DP to define fertilizer application over seven stages in a production season to maximize the value of the land parcel. Bontems and Thomas (2000) considered a farmer facing a sequential decision problem of fertilizer application under three sources of uncertainty: nitrogen leaching, crop yield and output prices. They used DP to maximize the farmer's profit per acre. Fertilization strategy was also evaluated in Thomas (2003), in which DP was used to evaluate the decision about applying nitrogen under uncertain fertilizer prices to maximize the expected value of the farmer's profit. Uncertainty may also come from specific products used in farm operations, such as herbicides, for which DP helped define the dose to be applied at each application (Pandey and Medd 1991). Facing uncertainty in water availability, Yaron and Dinar (1982) used DP to maximize farm income from cotton production on an Israeli farm during the irrigation season (80 days, divided into eight stages of ten days each), when soil moisture and irrigation water were uncertain. The results of a linear programming model to maximize profit at one stage served as input for optimization in the multi-period DP model with a backward process. Thus, irrigation strategy and the cotton area irrigated were selected at the beginning of each stage to optimize farm profit over the season. Bryant et al. (1993) used a dynamic programming model to allocate irrigations among competing crops, while allowing for stochastic weather patterns and temporary or permanent abandonment of one crop in dry periods is presented. They considered 15 intra-seasonal irrigation decisions on water allocation between corn and sorghum fields on the southern Texas High Plains. Facing external shocks on weed and pest invasions and uncertain rainfalls, Fafchamps (1993) used DP to consider three intra-year decision points on labor decisions of small farmers in Burkina Faso, West Africa for labor resource management at planting or replanting, weeding and harvest time.

Concerning animal production, decisions about herd management and feed rations were the main decisions identified in the literature to optimize farm objectives when herd composition and the quantity of biomass, stocks and yields changed between stages. Facing uncertain rainfall and consequently uncertain grass production, some authors used DP to decide how to manage the herd. Toft and O'Hanlon (1979) predicted the number of cows that needed to be sold every month over an 18-month period. Other authors combined reactive formalisms and static approaches to describe the sequential decision-making process from strategic decisions and adaptations to tactical decisions and adaptations. Strategic adaptations were considered reactive due to the difficulty in anticipating shocks and were represented with a recursive approach, while tactical adaptations made over a season were anticipated and described with static DSP. Mosnier et al. (2009) used DSP to adjust winter feed, cropping patterns and animal sales each month as a function of anticipated rainfall, beef prices and agricultural policy and then used a recursive process to study long-term effects (five years) of these events on the cropping system and on farm income. Belhouchette et al. (2004) divided the cropping year into two stages: in the first, a recursive process determined the cropping patterns and area allocated to each crop each year. The second stage used DSP to decide upon the final use of the cereal crop (grain or straw), the types of fodder consumed by the animals, the summer cropping pattern and the allocation of cropping area according to fall and winter climatic scenarios. Lescot et al. (2011) studied sequential decisions of a vineyard for investing in precision farming and plant-protection practices. By considering three stochastic parameters – infection pressure, farm cash balance and equipment performance – investment in precision farming equipment was decided upon in an initial stage with a recursive process. Once investments were made and stochastic parameters were observed, the DSP defined the plant-protection strategy to maximize income.

2.6. DISCUSSION

2.6.1. Adaptation: reactive or proactive process?

In the studies identified by this review, adaptation processes were modeled to address uncertainty in rainfall, market prices, and water supply, but also to address shocks such as disease. In the long term, uncertain events are difficult to anticipate due to the lack of knowledge about the environment. A general trend can be predicted based on past events, but no author in our survey provided quantitative expectations for future events. The best way to address uncertainty in long-term decisions is to consider that farmers have reactive behavior due to insufficient information about the environment to predict a shock. Adaptation of long-term decisions concerned the selling strategy, the cropping system and investments. Thus, in the research literature on farming system in agricultural economics and agronomy approaches, adaptation of strategic decisions is considered a dynamic process. In the medium and short terms, the temporal scale is short enough that farmers' expectations of shocks are much more realistic. Farmers observed new information about the environment, which provided more self-confidence in the event of a shock and helped them to anticipate changes. Two types of tactical adaptations were identified in the review: 1) medium-term adaptations that review decisions made for a season at the strategic level, such as revising the farm's selling or technical management strategies, and changing the cropping system or crop varieties; and 2) short-term adaptations (i.e., operational level) that adapt the crop operations at a daily scale, such as the cancellation, delay, substitution and addition of crop operations. Thus, in the research literature, adaptations of tactical decisions are mainly considered a static process.

2.6.2. Decision-making processes: multiple stages and sequential decisions

In Simon (1976), the concept of the decision-making process changed, and the idea of a dynamic decision-making process sustained over time through a continuous sequence of interrelated decisions (Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010) was more widely used and recognized. However, 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. Some authors used formalisms such as DP and DSP to describe sequential decision-making processes. In these cases, several stages were identified when farmers have to make a decision and adapt a previous strategy to new information. Sequential representation is particularly interesting and appropriate when the author attempts to model the entire decision-making processes from strategic to tactical and operational decisions; i.e., the complete temporal and spatial dimensions of the decision and adaptation processes (see section 2.5.3). For these authors, strategic adaptations and decisions influence tactical adaptations and decisions and vice-versa. Decisions made at one of these levels may disrupt the initial organization of resource availability and competition among activities over the short term (e.g., labor availability, machinery organization, irrigation distribution) but also lead to reconsideration of long-term decisions when the cropping system requires adaptation (e.g., change in crops within the rotation, effect of the previous crop). In the current agricultural literature, these consequences on long- and short-term organization are rarely considered, even though they appear an important driver of farmers' decision-making (Daydé et al. 2014). Combining several formalisms within an integrated model in which strategic and tactical adaptations and decisions influence each other is a good starting point for modeling adaptive behavior within farmers' decision-making processes.

2.6.3. What about social sciences?

Adaptation within decision-making processes had been studied in many other domains than agricultural economics and agronomy. Different researches of various domains (sociology, social psychology, cultural studies) on farmer behavior and decision-making have contributed to identify factors that may influence farmers' decision processes including economic, agronomic and social factors (Below et al. 2012; Wood et al. 2014; Jain et al. 2015).

We will give an example of another domain in social sciences that also uses these formalisms to describe adaptation. Computer simulation is a recent approach in the social sciences compared to natural sciences and engineering (Axelrod 1997). Simulation allows the analysis of rational as well as adaptive agents. The main type of simulation in social sciences is agent-based modeling. According to Farmer and Foley (2009) "An agent-based model is a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules." In agent-based models, farms are interpreted as individual agents that interact and exchange information, in a cooperative or conflicting way, within an agent-based systems (Balmann 1997). Adaptation in this regard is examined mostly as a collective effort involving such interactions between producers as economic agents, and not so much as an individual process. However, once the decision making process of a farmer has been analyzed for a particular cropping system, system-specific agent-based systems can be calibrated to accommodate for multiple farmer types in a given region (Happe et al. 2008). In agent-based models, agents are interacting with a dynamic environment made of other agents and social institution. Agents have the capacity to learn and adapt to changes in their environment (An 2012). Several approaches are used in agent-based model to model decision-making including microeconomic models and empirical or heuristic rules. Adaptation in these approaches can come from two sources (Le et al. 2012): 1) the different formalisms presented earlier can be used directly to describe the adaptive behavior of an agent, 2) the process of feedback loop to assimilate new situation due to change in the environment. In social sciences, farmers' decision-making processes are looked at a larger scale (territory, watershed) than articles reviewed here. Example of uses on land use, land cover change and ecology are given in the reviews of Matthews et al. (2007 and An (2012).

2.6.4. Uncertainty and dynamic properties

The dynamic features of decision-making concern: 1) uncertain and dynamic events in the environment, 2) anticipative and reactive decision-making processes, 3) dynamic internal changes of the decision process. In this paper we mainly talked about the first two features such as being in a decision-making context in which the properties change due to environmental, technological and regulatory risks brings the decision-maker to be reactive in the sense that he will adapt his decision to the changing environment (with proactive or reactive adaptation processes). Learning aspects are also a major point in adaptation processes. Learning processes allow updating and integrating knowledge from observation made on the environment. Feedback loops are usually used in agricultural economics and agronomy (Stengel 2003) and social sciences (Le et al. 2012). In such situations, learning can be represented by Bayes' theorem and the associated updating of probabilities. Two concerns have been highlighted on this approach: 1) evaluation of rare events, 2) limitation of human cognition (Chavas 2012). The state contingent approach presented by Chambers and Quiggin (2000; 2002) can provide a framework to investigate economic behavior under uncertainty without probability assessments. According to this framework, agricultural production under uncertainty can be represented by differentiating outputs according to the corresponding state of nature. This yields a more general framework than conventional approaches of production under uncertainty, while providing more realistic and tractable representations of production problems (Chambers and Quiggin 2002). These authors use state-contingent representations of production technologies to provide theoretical properties of producer decisions under uncertainty, although empirical applications still remain difficult to implement (see O'Donnell and Griffiths 2006 for a discussion on empirical aspects of the state-contingent approach). Other learning process approaches are used in artificial intelligence such as reinforcement learning and neuro-DP (Bertsekas and Tsitsiklis 1995; Pack Kaelbling et al. 1996).

2.7. CONCLUSION

A farm decision-making problem should be modeled within an integrative modeling framework that includes sequential aspects of the decision-making process and the adaptive capability and reactivity of farmers to address changes in their environment. Rethinking farm planning as a decision-making process, in which decisions are made continuously and sequentially over time to react to new available information, and in which the farmer is able to build a flexible plan to anticipate certain changes in the environment, is important to more closely simulate reality. Coupling optimization formalisms and planning appears to be an interesting approach to represent the combination of several temporal and spatial scales in models.

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TABLE CAPTION

Table 2.1: Modeling adaptive decision-making processes in farming systems; typology of the literature according to adaptation dimensions (temporal scope, spatial scope and timing scope) (DSP: discrete stochastic programming; DP: dynamic programming)

Adaptation dimensions			**Authors**	**Year**	**Formalism type**	**Formalism**
Temporal Scope	**Spatial Scope**	**Timing dimension**				
Strategic decisions (years)	Farm	Reactive	Barbier and Bergeron	1999	Dynamic	Recursive
	Farm	Reactive	Heidhues	1966	Dynamic	Recursive
	Farm	Reactive	Domptail and Nuppenau	2010	Dynamic	Recursive
	Farm	Reactive	Wallace and Moss	2002	Dynamic	Recursive
Tactical decision (season)	Farm	Proactive	Trebeck and Hardaker	1972	Static	DSP
	Farm	Proactive	Kingwell et al.	1993	Static	DSP
	Farm	Proactive	Jacquet and Pluvinage	1997	Static	DSP
	Farm	Proactive	Adesina and Sanders	1991	Static	DSP
	Farm	Proactive	Burt	1993	Static	DSP
	Farm	Proactive	Maatman and Schweigman	2002	Static	DSP
	Farm	Proactive	Ritten et al.	2010	Static	DSP
	Farm	Proactive	Detlefsen and Jensen	2007	Static	Flexible crop-sequence
	Farm	Proactive	Castellazzi et al.	2008	Static	Flexible crop-sequence
	Farm	Proactive	Dury	2011	Static	Flexible crop-sequence
Tactical decision (daily)	Plot	Proactive	Ripoche et al.	2011	Static	Optional execution
	Plot	Proactive	Martin et al.	2011	Static	Optional execution
	Plot	Proactive	Chardon et al.	2012	Static	Optional execution
	Plot	Proactive	Martin et al.	2011	Static	Optional execution
	Plot	Proactive	McKinion et al.	1989	Static	Proactive adjustments
	Plot	Proactive	Ripoche et al.	2011	Static	Proactive adjustments
	Plot	Proactive	Martin et al.	2011	Static	Proactive adjustments
	Plot	Proactive	Chardon et al.	2012	Static	Proactive adjustments
	Plot	Proactive	Rodriguez et al.	2011	Static	Proactive adjustments
	Plot	Proactive	Shaffer and Brodahl	1998	Static	Time windows
	Plot	Proactive	Cros et al.	1999	Static	Time windows
	Plot	Proactive	Crespo et al.	2011	Static	Time windows
	Plot	Proactive	Martin et al.	2011	Static	Time windows
Strategic & tactical decision (years & season)	Farm & Plot	Reactive	Reynaud	2009	Dynamic	DP
	Farm & Plot	Reactive	Stoecker et al.	1985	Dynamic	DP
	Farm & Plot	Reactive	Bryant et al.	1993	Dynamic	DP
	Farm & Plot	Reactive	Duffy and Taylor	1993	Dynamic	DP
	Farm & Plot	Reactive	Fafchamps	1993	Dynamic	DP

	Farm & Plot	Reactive	Hyytiäinen et al.	2011	Dynamic	DP
	Farm & Plot	Reactive	Bontems and Thomas	2000	Dynamic	DP
	Farm & Plot	Reactive	Thomas	2003	Dynamic	DP
	Farm & Plot	Reactive	Pandey and Medd	1991	Dynamic	DP
	Farm & Plot	Reactive	Yaron and Dinar	1982	Dynamic	DP
	Farm & Plot	Reactive	Toft and O'Hanlon	1979	Dynamic	DP
	Farm & Plot	Reactive & Proactive	Mosnier et al.	2009	Dynamic & Static	Recursive & DSP
	Farm & Plot	Reactive & Proactive	Belhouchette et al.	2004	Dynamic & Static	Recursive & DSP
	Farm & Plot	Reactive & Proactive	Lescot et al.	2011	Dynamic & Static	Recursive & DSP

FIGURE CAPTION

Figure 2.1: Adaptation of maize outputs after drought condition. At the beginning of the season, the farmer aims at growing maize for grain production. Due to dry conditions and low grass growth, the farmer has to use forage stocks to feed the herd, so that the stocks decrease. To maintain the stocks, the farmer has to adapt and change his crop orientation to maize silage.

FigureFigure 2.2: Typology of models to manage adaptive decision-making processes according to model type, approach, and formalism.

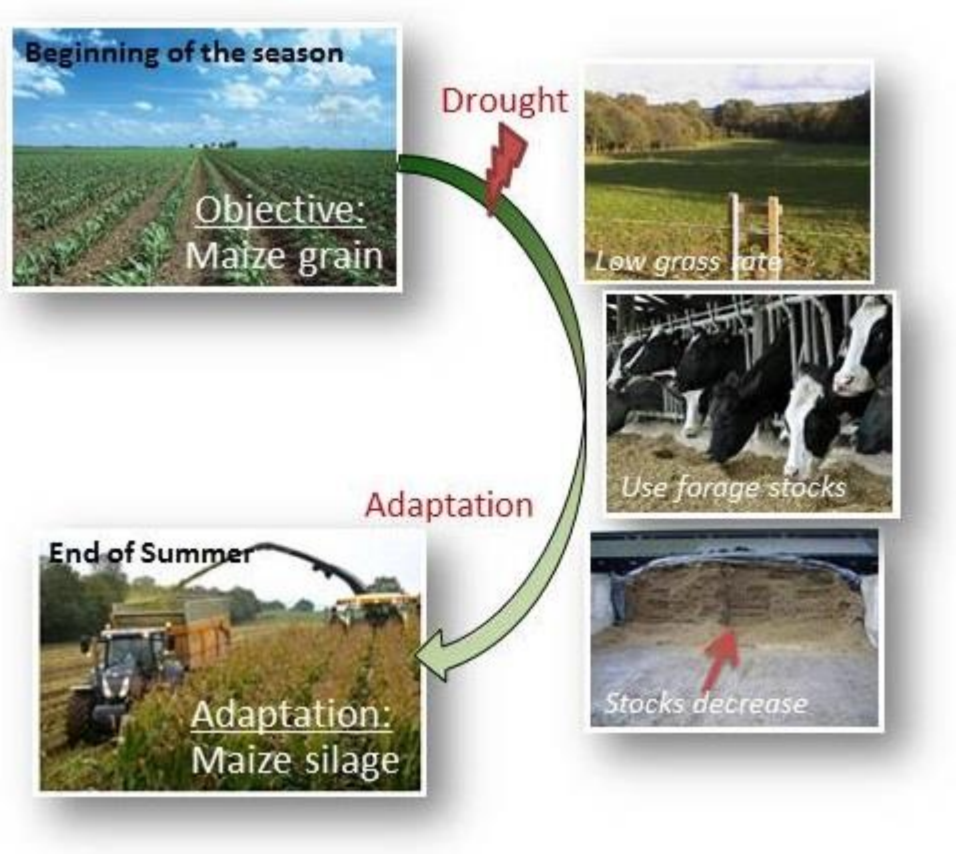
Beginning of the season
Objective:
Maize grain
Drought
Low grass rate
Use forage stocks
Stocks decrease
Adaptation
End of Summer
Adaptation:
Maize silage

Figure 2.1

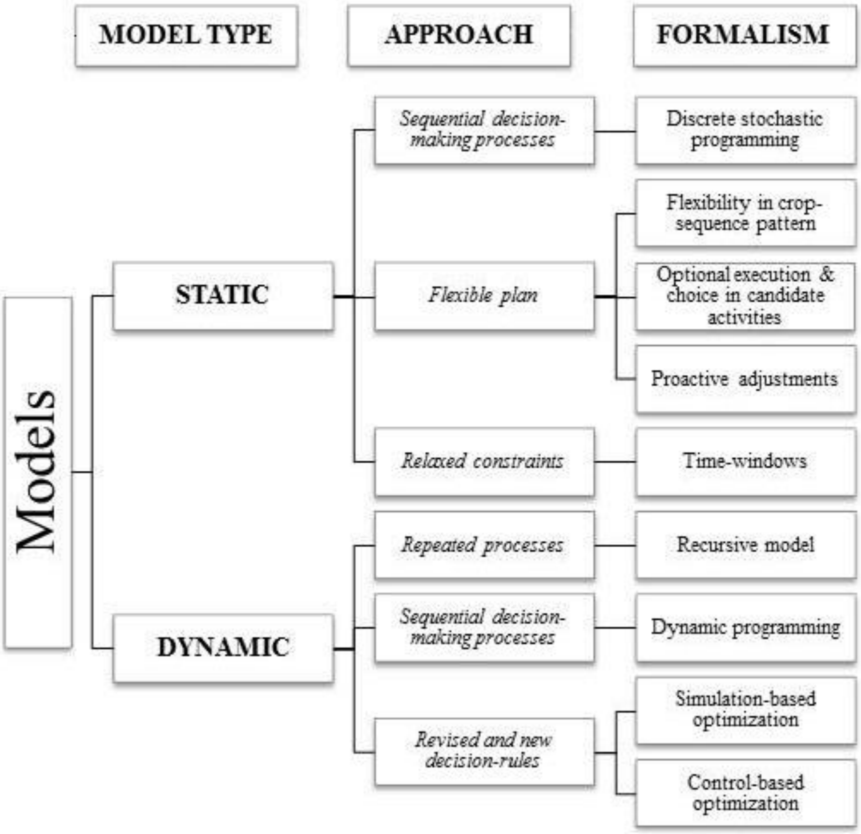
MODEL TYPE
APPROACH
FORMALISM
Models
STATIC
DYNAMIC
Sequential decision-making processes
Discrete stochastic programming
Flexibility in crop-sequence pattern
Flexible plan
Optional execution & choice in candidate activities
Proactive adjustments
Relaxed constraints
Time-windows
Repeated processes
Recursive model
Sequential decision-making processes
Dynamic programming
Simulation-based optimization
Revised and new decision-rules
Control-based optimization

Figure 2.2

Chapter 3

Farm typology in the Berambadi watershed (India): farming systems are determined by farm size and access to groundwater

Marion Robert*[1], Alban Thomas[2], Muddu Sekhar[3,6], Shrinivas Badiger[4], Laurent Ruiz[5,6], Magali Willaume[1], Delphine Leenhardt[1] and Jacques-Eric Bergez[1]

[1]AGIR, Université de Toulouse, INPT-ENSAT, INRA, F-31326 Castanet-Tolosan, France
[2]INRA, Toulouse School of Economics, UMR 1415 TSE-R, F-31000 Toulouse, France
[3]Indian Institute of Sciences, Department of Civil Engineering, Bangalore 560012, India
[4]ATREE, Bangalore 560064, India
[5]INRA, Agrocampus, UMR 1069 SAS, F-35042 Rennes, France
[6]Indo-French Cell of Water Sciences, IRD-IISc, Bangalore, India

* Corresponding author: (marion.robert@inra.fr)

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Farmers' production decisions and agricultural practices directly and indirectly influence the quantity and quality of natural resources, some being depleted common resources such as groundwater. Representing farming systems while accounting for their flexibility is needed to evaluate targeted, regional water management policies. Farmers' decisions regarding investing in irrigation and adopting cropping systems are inherently dynamic and must adapt to changes in climate and agronomic, economic and social, and institutional, conditions. To represent this diversity, we developed a typology of Indian farmers from a survey of 684 farms in Berambadi, an agricultural watershed in southern India (state of Karnataka). The survey provided information on farm structure, the cropping system and farm practices, water management for irrigation, and economic performances of the farm. Descriptive statistics and multivariate analysis (Multiple Correspondence Analysis and Agglomerative Hierarchical Clustering) were used to analyze relationships between observed factors and establish the farm typology. We identified three main types of farms: 1) large diversified and productivist farms, 2) small and marginal rainfed farms, and 3) small irrigated marketing farms. This typology represents the heterogeneity of farms in the Berambadi watershed. Used within a simulation model of the watershed, this typology should enable policy makers to better assess potential impacts of agricultural and water management policies on farmers' livelihood and the groundwater table.

Keywords: farm typology, Multiple Correspondence Analysis, Agglomerative Hierarchical Clustering, Berambadi watershed

3.1. INTRODUCTION

In semi-arid regions, agricultural production systems depend greatly on irrigation and encounter increasing challenges: growing uncertainty about how to respond to climate change, severe depletion of natural resources, high volatility in market prices, rises in energy costs, greater pressure from public regulations (agricultural, environmental, and health policies), and conflicts about sharing communal water resources (Ragab and Prudhomme 2002). Policies to improve agricultural water use efficiency are often found to be inefficient when there are designed without taking into account the whole system, including farmer's choices, as shown for example by Fishman, Devineni, and Raman (2015) in the case of irrigation technologies. Modeling farming systems at regional scale is a relevant approach to assess "ex-ante" targeted water management policies (Valverde et al. 2015; Graveline 2016). However, as modeling all individual farms within a region is usually not feasible, such approaches requires building a farm typology (Köbrich et al. 2003) representing in a simplified way the existing diversity of farming systems while accounting to the possible differential response of farm types to management policies.

A typology is an artificial way to define different homogeneous groups, categories or types based on specific criteria in order to organize reality from a viewpoint relevant to the objectives of the model (Duvernoy 2000; Andersen et al. 2007; Valbuena et al. 2008). Typologies are a convenient tool to simplify the diversity of farming systems while effectively describing their heterogeneity (Poussin et al. 2008; Valbuena et al. 2008; Daloğlu et al. 2014). Since farm types are adapted to local restrictions such as resource availability, it is also necessary to identify their spatial distribution or location factors (Clavel et al. 2011).

Building such typologies is particularly challenging in the case of India. During the "green revolution" that started in the 1970s, development of irrigation was mostly concentrated in the command area of dams, and the construction of large dams has been promoted (Pani 2009). Later, the development of submersible pump technology in the 1990s resulted in a dramatic increase of the irrigated agricultural area (Sekhar et al. 2006; Javeed et al. 2009). This shift from collective ponds (Dorin and Landy 2002; Chandrasekaran et al. 2009) to individual borewells has been largely encouraged by public policies that provide farmers free electricity for groundwater irrigation (Shah et al. 2012). This shift caused agricultural practices to depend heavily on irrigation from groundwater (Aubriot 2013) and induced a well-identified "groundwater crisis" with tremendous impacts on water resources and ecosystems. Today, millions of small farms (less than one hectare, on average) owning individual borewells, with great diversity in practices and strategies (Sekhar et al. 2011) are spread in areas where only rainfed agriculture was possible few years ago. In such a context, modeling and quantifying spatio-temporal variability in water resources and interactions among groundwater, agricultural practices and crop growth, which is an essential component of integrated and comprehensive water resource management, is a challenge (Venot et al. 2010; Ruiz et al. 2015).

In this article, we generate a typology of farms and spatialize farm types in the Berambadi watershed (84 km²), located in Southern India. This site was selected because it is small enough for accurate monitoring and large enough to include a large portion of the variability in agricultural systems within the region. Identifying and understanding variability in farm characteristics and farming practices on the watershed, based on farmer surveys, provide us relevant criteria for proposing possible scenarios of farming system evolution in the watershed, that could be later simulated in watershed models.

3.2. MATERIALS AND METHODS

3.2.1.Case study: Hydrological and morphological description of the watershed

Berambadi (11°43'00” to 11°48'00" N, 76° 31'00" to 76° 40'00" E) is an 84 km² watershed located in southwestern India. It belongs to the South Gundal basin, 816 km2, part of the Kabini River basin (approximately 7000 km², southwestern Karnataka state), which is a tributary of the Kaveri River basin (Figure 3.1). Biophysical variables have been intensively monitored since 2009 in the Berambadi watershed, under the Environmental Research Observatory ORE BVET (http://bvet.obs-mip.fr/en) and the AMBHAS observatory (Sekhar et al. 2016; Tomer et al. 2015, www.ambhas.com).

Due to the rain shadow of the Western Ghats during the southwestern monsoon rains, the Kabini basin exhibits a steep rainfall gradient, from a humid zone in the west with more than 5000 mm of rain per year to a semi-arid zone in the east with less than 700 mm of rain per year. Since the Berambadi watershed is located in the eastern Kabini basin, its climate is tropical sub-humid (aridity index P/PET of 0.7), with rainfall of 800 mm/year and PET of 1100 mm per year, on average (Sekhar et al. 2016). A moderate east-west rainfall gradient is observed at the watershed scale, with approximately 900 mm rainfall per year upstream (west) and less than 700 mm rainfall per year downstream (east). Three seasons regulate the cropping systems: 1) kharif (June to September), which is the southwestern monsoon season, when almost all plots are cultivated and are either exclusively rainfed or have supplemental irrigation; 2) rabi (October to January), the northeasten monsoon or winter season, when most of the plots where irrigation is possible are cultivated; and 3) summer (February to May), the hot and dry season, when only few irrigated plots are cultivated.

Black soil (Vertisols and Vertic intergrades), red soil (Ferrasols and Chromic Lusivols) and rocky/weathered soil are the main soil types in the area and represent the granitic/gnessic lithology found in southern India (Barbiéro et al. 2007). The hard-rock aquifer is composed of fissured granite underlain by a 5-20 m layer of weathered material. Groundwater transmissivity and borewell yields decrease with groundwater table depth (Maréchal et al. 2010). As a consequence, continuous pumping causing groundwater table drawdown leads to a disproportionate decrease of the amount of groundwater available for irrigation (Dewandel et al. 2010; Perrin et al. 2011). This positive feedback loop makes predefined land-use scenarios unrealistic, since farmers need to adapt their actions continually according to groundwater availability (Ruiz et al. 2015).

Water table levels display a pattern that is atypical in hydrology: valley regions have deeper groundwater table levels than topographically higher zones. Thus, an unusual groundwater level gradient is observed; with a shallow groundwater table upstream and deep groundwater table downstream (Figure 3.1). This pattern is the result of intensive groundwater pumping since the early 1990s in villages located in the valley (where soils are more fertile) (Sekhar et al. 2011). The low cost of pumping water and subsidies for irrigation equipment encouraged farmers to drill more borewells (Shah et al. 2009). This dramatic change is closely linked to the spatial distribution of soil types and groundwater availability, as well as farming practices, access to the market, knowledge, new agricultural and know-hows, and government aid (Sekhar et al. 2011).

An increasing number of farmers report borewell failures for two main reasons: borewells have run dry after excessive pumping, or no water was found in newly drilled borewells (González Botero and Bertran Salinas 2013). The decrease in groundwater table level disconnected groundwater table from river beds, turning main permanent rivers into ephemeral streams, which has occurred to other rivers in the region (Srinivasan et al. 2015). Wells have recently been drilled in upland areas, where groundwater irrigation is increasing.

3.2.2. Survey design and sampling

The farmland ownership register (Bhoomi) of Karnataka lists farmers and land ownership for each village in Karnataka. The Berambadi watershed contains 5461 farm households distributed in 12 villages. To identify how many and which farms to survey in this agrarian community, we used purposive stratified proportional sampling. This sampling procedure is used to estimate distribution parameters for a heterogeneous population (Laoubi and Yamao 2009; Levy and Lemeshow 2013). The main advantage of this sampling approach is a better representation of the population than other probability methods like simple random sampling or systematic sampling (Laoubi and Yamao 2009). Indeed, with stratified sampling, even the smallest subgroup in the population can be represented while selecting a relatively small sample size (Rossi et al. 2013). This ensures that every category of the population is represented in the sample. A stratified sample recreates the statistical features of the population on a smaller scale (Cochran 1953). In stratified proportional sampling, the sample size of each stratum must be proportional to the population size of the stratum meaning that each stratum has the same sampling fraction. The size of the sample selected from each stratum per village was proportional to the relative size of that stratum in the farmer population. As such, the sampling procedure is self-weighting and an equal-probability-of-selection method. The same sampling proportion was applied to each stratum, giving each element in the population an equal chance of selection. In our farmer population, we stratified the farmers based on the land ownership of farmers. That is, farmers were considered as marginal, small, medium or large owners (e.g. variable totalHHSize in Table 3.1).

The samples were purposefully selected to represent the caste diversity in the region. In total, 684 farm households, which represent 12.5% of farms on the watershed, were interviewed from September 2014 to March 2015. The survey consisted of a face-to-face interview lasting 2-3 hours. The survey was divided into three parts. The first part focused on household characteristics, farm structure, assets, partnerships, and farm objectives. In the second part, we asked farmers about their performances and practices over the past two years (2013-2014). The absence of a record of past practices made it difficult to obtain data on past cropping systems and farm activities that occurred more than two years ago. Incomes from selling crops were available for 2013. Concerning farm expenditure, farmers were comfortable in providing information for the most recent cropping season – kharif 2014. In the last part, in-depth questions were asked about irrigation, borewells, and rainfall. Since no yearly records were kept by farmers, information about historical management went no further than the past two years.

3.2.3. Analysis method

First, we identified variability in farm characteristics and farming practices on the watershed, based on farmer surveys. Four dimensions were analyzed: 1) farm structure, 2) the cropping system and farm practices, 3) water management for irrigation, and 4) economic performances of the farm. To examine the variability and spatial pattern of each dimension on the watershed, we used the village as the spatialized indicator. To determine the overall significance of differences among villages, the means of the qualitative variables were compared by an analysis of variance (ANOVA) permutation test whereas the independence between qualitative variables were tested by chi-square tests. We considered the differences among villages significant at the 95% level. Analyses were performed with the R language and environment for statistical computing (R Core Team 2013).

Second, we used the results of the previous analysis to establish a typology of farms based on the farm characteristics and farming practices describing some variability on the watershed. We performed a two-step statistical analysis. The first step used the nominal categorical data technique of Multiple Correspondence Analysis (MCA). MCA is an extension of correspondence analysis for more than two variables. Compared to principal component analysis, MCA allows the use of both quantitative and qualitative variables. The non-correlated quantitative variables were converted into qualitative variables with associated modalities (classes) and then used for MCA analysis. (Le Roux and Rouaner 2004; Husson et al. 2010). However, transforming quantitative variables into qualitative ones may lead to a loss of some of its properties as well as the measurement precision. The principle of MCA is to define factors representing an optimized quantitative summary of the relationships between variables (Di Franco 2016). Compared to other statistical methods, MCA has some interesting advantages. The MCA procedure does not require any preconditions on variables (such as multivariate normality or linearity) and it offers statistical results that can be seen both analytically and visually. The MCA is a preprocessing step for the classification or typology purposes. It provides qualitative values derived from categorical variables needed in deterministic cluster analysis (Kristensen et al. 2004). The principal components of the MCA were then used as input variables in an Agglomerative Hierarchical Clustering (AHC) algorithm. It starts with as many clusters as farms and progressively sorts the farm by building up a tree from successive merges of the two nearest clusters. The AHC procedure is often represented by a two dimensional diagram (dendrogram) which illustrates the classification obtained at each successive stage of the analysis. This method successively groups the closest farms into clusters, which then are grouped into larger clusters of higher rank (farm types) by partitioning farms based on their factorial coordinates using the Ward's minimum-variance aggregation method criterion for minimizing intra-cluster variance and maximizing variance between clusters (Omran et al. 2007; Kaufman and Rousseeuw 2009).

The farm types can then be described by the quantitative variables with the coefficient of determination and the p-value of the F-test in a one-way ANOVA (assuming homoscedasticity).

3.3. Variability and spatialization of farm characteristics and practices

3.3.1. Farm structure

Household characteristics

At the Berambadi watershed scale, three gram Panchayats[2] were identified: i) Bheemanabeedu gram panchayat for the eastern villages, ii) Kannagala gram panchayat for the central villages and iii) Berambadi gram panchayat for the western villages. The eastern portion of the watershed is statistically dominated by the Upparas sub-caste, and the central and western portions consist mainly of the Schedule Caste and Lingayat (Figure 3.2).

The average household in the watershed is composed of four adults (2 men and 2 women) and one elder person (> 60 years old). Overall, 86% of households investigated are headed by a man of 58

[2] The Panchayat is the system of local self-government. The basic unit of the Panchayats in India is known as the 'gram Panchayat' (Paul and Chakravarty 2016), namely the village council that is elected in the popular voting system. The principal functions performed by the gram Panchayats are maintaining roads, wells, schools, burning and burial grounds, sanitation, public health, libraries, reading rooms, community centers, etc.

years of age, on average, who is usually illiterate (61% of heads-of-household are illiterate). Men usually work full-time on the farm, while women work part-time on the farm and perform the domestic work. Agricultural labor is a secondary occupation for 16% of the interviewed population. Few people migrate to work in other places during rabi season (people migrate in only 4% of households). Households in the Berambadi gram panchayat are statistically smaller, with three adult members and one elderly person. A larger percentage of farmers are better educated in the Kannegala gram panchayat, and over 50% attended at least pre-primary school (vs. 20% in the rest of the watershed) (Figure 3.2).

Land holding

Average farm size in the watershed is 1.2 hectares and varies from 0.01-9.3 hectares. Most farms are small (48% have 0.8-2 hectares) or marginal (32% have < 0.8 hectares). Only 17% of farms have more than 2 hectares, while 3% have more than 4 hectares. Farmers own their farmland. A field with adjacent agricultural plots cultivated by the same farmer is called a “jeminu”. A farm can comprise several “jeminus”, which may or may not be located nearby each other; they can even be located in different villages. Overall, 45% of farmers have only one jeminu, while 26% have 2, 13% have 3 and 16% have more than 3. The entire jeminu can be dedicated to one crop each season (54%) or divided into several crop plots (31% with 2 crop plots, 14% with 3-5 crop plots). On average, a crop plot is 0.4 hectare but varies from 0.01-2.4 hectares.

Land holding is variable on the watershed. Statistically, more marginal farms (< 0.8 ha) exist in the Beemanabeedu gram panchayat (42%, vs. 23% in the rest of the watershed), where farms are more fragmented (80% of farms in the Beemanabeedu gram panchayat have more than 1 jeminus vs. 55% in the rest of the watershed). Farms in the Berambadi gram panchayat are less diversified: 80% cultivate only one plot with one crop (vs. 60% in the rest of the watershed) (Figure 3.2).

Livestock and equipment

Even though livestock production is usually a secondary activity, farmers have animals for traction, milk, meat and breeding. To represent the livestock intensity we built a coefficient of Tropical Livestock Unit (TLU) where cows, oxens, buffalos, and bulls are 1 TLU and sheep and goats equal 0.2 TLU (Meyer 2016). Farmers have an average of 2 TLU.

The traditional equipment for soil operations is based on animal traction. Motorization recently spread, and plowing with a tractor now commonly supplements the traditional animal work. However, tractors are expensive, and most farmers (94%) prefer to rent from a tractor owner in the village rather than obtaining a loan to buy one. Farmers use oxen, bulls and buffalos along with a plow (96% use a plow and 87% own one). Farmers who own animals for traction usually have only one pair of animals. A pesticide sprayer is the most common equipment used for farming operations in the Berambadi watershed (88% use a sprayer and 61% own one). Seeders, weeders and rotovators are rarely owned or used in the watershed. Seeding, fertilizing, weeding and harvesting are usually performed manually and do not require specific equipment.

Equipment use varies spatially across the watershed. The percentage of farmers owning buffalos is statistically the highest in the Kannegala and Berambadi gram panchayats. Statistically, a pesticide sprayer is owned mainly by farmers in the Beemanabeedu and Berambadi gram panchayats. Livestock ownership varies statistically across the watershed: more than 50% of farmers own at least 2 TLU in the Kannegala and Berambadi gram panchayats, while 20% of farmers own at least TLU in the Beemanabeedu gram panchayat (Figure 3.2).

Labor

Because many technical operations are manual, farming practices are highly labor-intensive. Only two farmers employ permanent workers; they hire workers on a daily basis or based on crop-operation contracts. Women typically perform sowing, weeding and harvesting, and men typically perform soil preparation, fertilization, pesticide treatment and irrigation. In 2013 and 2014, 40 male workers and 84 female workers were hired on average per hectare for the cropping season. No significant spatial variability was found in labor per hectare across the watershed.

3.3.2. Farm practices

Input use

The amount of input purchased per unit of cultivated area decreases on a northwest-southeast gradient. Villages from the Berambadi gram panchayat have higher expenses for pesticides (3750 Rs/hectare) and chemical fertilizers (6250 Rs/hectare). The percentage of farms that do not use manure is also statistically higher (40-80%) in villages from the Berambadi gram panchayat, which reinforces dependency on chemical inputs. While the purchase of pesticides strongly decreases along this gradient (reaching only 750 Rs/hectare in the Beemanabeedu gram panchayat), the decrease in the purchase of chemical fertilizer is lower (from 6250 to 4500 Rs/hectare) (Figure 3.2).

Crop yield performances

Crop yields vary greatly among fields. However, high-input villages from Berambadi gram panchayat and low-input villages from Beemanabeedu gram panchayat have particularly low yields (< 2.5 t/hectare, on average, for rainfed sorghum, or irrigated maize). Villages in the Kannegala gram panchayat have statistically better results, (> 2.5 t/hectare, on average and up to 10 t/hectare for for the same crops) (Figure 3.2). In villages from the Kannegala and Berambadi gram panchayats, more than 30 and 35% of farming areas are grown for subsistence whereas only 5% of the farming areas of villages from the Beemanabeedu gram panchayat are grown for subsistence.

3.3.3. Water management for irrigation

Access to irrigation

Overall, 59% of farms have access to irrigation. Irrigated farms have on average more jeminus than non-irrigated farms: 32% of irrigated farms vs. 63% of non-irrigated farms have only one jeminu. Farms with only one jeminu are mainly rainfed (58%), while 73% of farms with more than one jeminu are irrigated. For 63% of irrigated farms, all the jeminus have access to irrigation. All the surveyed farms with access to irrigation directly use groundwater on their fields or temporarily store it in individual farm ponds. We observed only a few cases of exchange or sale of water between farmers. Statistically, more irrigated farms exist in the Beemanabeedu gram panchayat, where they represent approximately 80% of the farms.

Borewells

The first borewells in the watershed were drilled in the 1970s, and borewell drilling has increased dramatically since the mid-1990s. In our sample, 31 borewells were drilled before 1995, and 470 borewells were drilled after 1995. In the 1970s and 1980s, most borewells were drilled in the Beemanabeedu and Kannegala gram panchayats, while in the Berambadi gram panchayat well drilling occurred mainly in the 2000s. In addition to the increasing number of borewells, technology has allowed drilling deeper wells. The maximum depth of wells drilled before 1995 was 150 m, while 15% of the borewells drilled from 1995-2010 were deeper than 150 m. Among the 214 borewells drilled after 2010, 25% were deeper than 150 m, with the deepest reaching 250 m.

From the survey sample of 1192 borewells, 33% were working at the time of the survey, while 58% had failed (i.e. produced no water), and 9% had been temporarily stopped since 2013. No relation was found between the depth of a borewell and whether it worked, had been stopped or had failed. There are as many farms with at least one no working borewell as farms on which all borewells work (115 and 105 farms, respectively, of the 245 farms that had drilled at least one borewell). Overall, 49 farms (7%) that attempted to drill borewells never got groundwater for irrigation.

Figure 3.3 summarizes the spatial distribution of irrigated farms and their borewell characteristics within the watershed. Each farm has drilled approximately 3 borewells in the Beemanabeedu gram panchayat vs. less than one in the Berambadi gram panchayat, which is consistent with irrigated farms being located predominantly in the Beemanabeedu gram panchayat villages. However, borewell failure has occurred predominantly in the Beemanabeedu gram panchayat villages (more than 65% of borewells drilled in the Beemanabeedu gram panchayat villages have failed, vs. 53% in the Kannegala gram panchayat villages, and 35% in Berambadi gram panchayat villages), which results in a relatively uniform number of working borewells per farm within the watershed.

Pumps and access to electricity

Farmers use electric pumps, mostly of 7.5 horse power (HP). Farmers who need electricity, i.e. those with at least one working borewell, have approximately 3-4 hours of electricity per day during kharif and 2-3 hours per day during rabi, with on average 2-4 power outages per day. The duration of electricity supply during kharif is statistically higher in the Kannegala gram panchayat villages, where 69% of farms have more than 4 hours of power per day. Electricity is usually available less than 4 hours per day in the rest of the watershed (Figure 3.2).

Farm ponds

Farm ponds are shallow ponds in which farmers store pumped water for distribution throughout the day, especially during power outages at critical times. It takes 2-9 hours to fill a farm pond. Approximately 290 individual farm ponds exist on the surveyed farms, and only 36% of farms have one. No relationship was found between farm pond ownership and location on the watershed.

Irrigation methods

Among irrigated farms, 81% use only one irrigation method. Furrow irrigation is by far the most common method (75% of irrigated farms), mainly as the only irrigation method (58%), and more rarely is used in combination with a sprinkler or drip (17%). Among alternative methods of irrigation, sprinklers (17% of the jeminus) are used more often than drip irrigation (3% of the jeminus) or flood irrigation (2% of the jeminus). Sprinkler irrigation statistically occurs more in the Beemanabeedu gram panchayat villages (37-78% of jeminus, depending on the village), while the Berambadi gram panchayat villages almost exclusively used furrow irrigation (94% of jeminus) (Figure 3.2).

3.3.4. Economic performances of the farm

Investment in farm structure

Considering investments in equipment and livestock, farmers owned an average of 4500 Rs/hectare of equipment 18,670 Rs/TLU of livestock at the time of the survey. On average in 2013-2014, farmers hire 22,100 Rs/hectare of labor each cropping season, with male wages fixed at 250 Rs/day and female labor at 150 Rs/day. The only clear statistical difference in investment in farm structure is the livestock investment, which is slightly higher in the Kannegala and Berambadi gram panchayat villages than in the Beemanabeedu gram panchayat villages due to greater use of animal traction for cultivation.

Cropping systems' products and expenses

Fertilizers and pesticides cost approximately 12,700 Rs/hectare during kharif 2014. Overall, 99% of farmers buy some or all of their inputs from retailers, 8% purchase some of their inputs from a cooperative and 64% obtain them from government suppliers. A higher percentage of farmers obtain inputs from a cooperative in the Berambadi gram panchayat villages (> 25%), whereas a lower percentage do so in the Kannegala and Beemanabeedu gram panchayat villages. Selling crops during kharif yield an average of 39,900 Rs/hectare in 2013. For kharif, no difference is observed across the watershed. Only 74% and 9% of farmers sell cash crops during rabi and summer, respectively. Rabi crops earn approximately 9630 Rs/hectare, while summer crops earn approximately 25,750 Rs/hectare in 2013. A statistically higher percentage of farmers grow cash crops during rabi in the Beemanabeedu gram panchayat villages, where more than 50% earn more than 12,500 Rs/hectare during rabi, vs. less than 30% in the Berambadi gram panchayat villages.

Investment in irrigation

Investment in a borewell is based on its depth. The deeper the borewell is, the more it will cost to drill. However, borewell drilling has a fixed cost per meter (approximately 410 Rs), regardless of the depth at which drilling begins. Farmers typically maintain a borewell five years after drilling it (62% of borewells, while 24% are maintained 5-10 years after drilling). Maintenance costs approximately 6000 Rs per borewell over the borewell life. Investment in pumps varies. The main investment is 7.5 HP pumps (61%), which at approximately 28,000 Rs, cost 3000-7000 Rs more than pumps with less HP. Investments linked to water management do not vary across the watershed.

3.4. TYPOLOGY OF FARMS IN THE BERAMBADI WATERSHED

3.4.1. Characteristics of farm typology

The survey identified nearly 50 qualitative and quantitative variables on the farming context, farm performance and farming practices. Following the previous analysis and after checking for correlation and homogeneity among the households, we tested 12 variables in the MCA (Table3.1). The variables that had less weight on the four first axes were used as complementary variables. Variables that describe the farming context included those related to the spatial location of the farm and resources for the farmland, irrigation and animals. Farm location is described by the village. The 12 villages in the watershed were combined into five ‘big’ villages (V1, V2, V3, V4, V5) based on similarities in their groundwater tables. The land-resource variables (3) are farm size, number of jeminus and number of plots. The irrigation-resource variables (4) are access to irrigation, the number of failed and working borewells and hours of electricity available per day for pumping. The animal resource is summarized into the class of livestock variable. Variables that describe the farm performances include those related to production costs (input costs spent per hectare in kharif 2014) and incomes (rabi incomes per hectare in 2013). Farming practices are included in the cropping system variable, which distinguishes cropping systems by irrigation practice and crop purpose (cash crop or subsistence).

The first two components of the MCA explain 25.9 % of the total variability in individuals (Figure 3.4). The third and fourth components explain 8.1 % and 7.1% of the total variability in individuals, respectively. The first axis discriminates 1) rainfed farms that grow rainfed crops without access to irrigation water and 2) irrigated farms that grow mixed crops based on irrigation water from borewells and access to electricity (Figure 3.4). The second axis discriminates 1) large farms (S(+)) with several jeminus (J3+) and several plots that use water from borewells located in the center of the watershed (V3 and V4), where electricity is more available (hours(4+)) and that grow irrigated and rainfed crops for cash and subsistence purposes (CS5 and CS2) from 2) smaller farms (S(-) and S(--)) located in the eastern and western portions of the watershed (V1, V2 and V5) that grow crops on one or two plots (J1 and J2) as a cash crop (CS4 and CS3) and have less available electricity (hours(2-3) and hours(4)).
The MCA allowed us to reduce the number of dimensions in the qualitative data by selecting the first 12 components of the MCA, which collectively explained 79.1% of the total variation. The first 12 principal components in an AHC algorithm were then used as input variables in an Agglomerative Hierarchical Clustering (AHC) algorithm. The choice of the number of clusters for the partition was made relative to the general shape of the tree, the gain of inertia between the clusters when adding a cluster and the interpretability of the clusters. To identify the number of farm types (clusters) we identified the maximum jump in between-cluster inertia (Norusis 2012) (Figure 3.5). We obtained a typology with three farm types (Figure 3.5). Three groups are clearly distinguishable on the projection of individuals in the plane of the first complete MCA (Figure 3.6).

3.4.2. Characteristics of the farm types

Characteristics and homogeneity of the three farm types identified based on the survey data are presented in Table 3.2.

Farm type 1: Large diversified and productivist farms

Type 1 farms are located mainly in the center of the watershed (73% of type 1 farms are in V3, where 36% of farms are type 1) (Figure 3.7 and Table 3.2). This type represents all large farms in the sample and some medium farms (39% of type 1 farms are medium) with the highest amount of electricity available for pumping (56% of type 1 farms have > 4 hours per day). Overall, 56% of type 1 farms have more than 2 hectares of land. These large farms are often composed of several jeminus where farmers can easily cultivate several plots. Nearly all type 1 farms have the same water access. Overall, 97% of these farms are irrigated from one or more borewells. However, access to groundwater for irrigation is risky and costly; 64% of these farms also experienced borewell. Overall, 88% of these farms graze livestock to provide animal traction and manure. Input costs and income from selling cash crops are diversified in this farm type. Farming practices are diversified, with cropping systems that mix irrigated and rainfed crops grown as cash crops or for subsistence (53% in CS5) or as cash crops only (19% in CS3 and CS4).

Farm type 2: Small and marginal rainfed farms

Type 2 includes marginal and small rainfed farms located in the central (39% of type 2 farms are in V3) and western portions of the watershed (45% of type 2 farms are in V4 and V5) (Figure 3.7 and Table 3.2). More than 90% of these farms have less than 2 hectares on one jeminu and operate on 1-2 plots. They have no access to irrigation, and few have ever attempted to drill a borewell. Due to the absence of irrigation, it is difficult to grow crops during rabi (62% earned < 37,000 Rs/hectare in 2013). These small farms have the lowest farming expenditures (64% invested < 7,400 Rs/hectare in fertilizers and pesticides during kharif in 2014). While 65% grow only cash crops, the other 35% grow also subsistence crops to cover household needs.

Farm type 3: Small irrigable marketing farms

Type 3 consists of small irrigated farms located in the eastern portion of the watershed (72% are in V1 and V2) (Figure 3.7 and Table 3.2). Overall, 85% of type 3 farms have less 2 hectares on one jeminu and operate on 1-2 plots. Farmers have at least one borewell, and 67% have experienced a failed borewell. Electricity for pumping is less available in this portion of the watershed than in the center (type 1). In general, farmers have medium to large expenses balanced by medium to large incomes from selling crops. Cropping systems are diversified by mixing irrigated and rainfed crops, but all production is reserved for cash crops (91% of farms in CS3 and CS4).

3.5. DISCUSSION

Irrigation technology developed after 1995 greatly influenced groundwater table depletion in the Berambadi watershed. In addition to this technological development, expected future change in regional climate might lead to higher evapotranspiration which could result in decrease of groundwater recharge. To preserve the depth of the groundwater table and minimize its depletion due to agricultural practices, a variety of policy interventions are possible for promoting water-management practices that reduce pumping and groundwater depletion, including changing the conditions of electricity supply for irrigation or promoting water-efficient crops or irrigation techniques. However, to be efficient and accepted by farmers they should be adapted to farm characteristics and objectives.

Farm typologies are critical for representing while also simplifying the diversity of farms in a large area. Specifically, farm typologies are critical to effectively represent the heterogeneity of farmers' objectives and socio-eco-agronomic conditions relative to their decision-making processes regarding farm management. The sample selection and statistical analysis used to generate the typology may influence the latter's quality. Access to the Karnataka land-ownership register was critical for identifying a sample that statistically represented the population of the watershed based on farmers' land ownership. The survey process was in the local language, which made it difficult to understand specific agronomic terms and concepts. The absence of a record of past practices made it difficult to obtain data on past cropping systems and farm activities that occurred more than two years ago. The data obtained were based mainly on farmers' reports. Except for village affiliation, no other spatial indicator was collected in the survey. An important issue in the field was obtaining the exact location of a farm within a village.

The combination of multivariate statistical techniques and cluster analysis is widely used in characterization studies and farm-typology studies (e.g. Goswami et al. 2014; Laoubi & Yamao 2009; Milán et al. 2006; Kristensen et al. 2004). Goswami et al. (2014) combined principal component analysis with a hierarchical method and a K-means clustering method to develop a typology of farms and economic characteristics in India. Laoubi & Yamao (2009) used MCA and AHC to develop a typology of irrigated farms in Algeria. Milán et al. (2006) used MCA and cluster analysis to develop a typology of beef-cattle farms in Spain. Kristensen et al. (2004) developed a typology of farms, farmer characteristics and landscape changes in Denmark by combining MCA and AHC.

The Berambadi watershed is a small region where farms had certain characteristics that were relatively similar, unlike other studies conducted at state or district levels. For instance, household composition and organization (i.e. family size, family members' main occupation, and migration) were similar in the Berambadi watershed. Goswami et al. (2014) conducted a study at the district level in the South 24 Parganas district in West Bengal, and Senthilkumar et al. (2012) conducted a study at the state level in

Tamil Nadu (the neighboring state to the south of Karnataka). Both studies showed that family size and off-farm income were heterogeneous in larger regions. Seasonal migration of rural labor is a common problem in rural India (Deshingkar and Start 2003; Chandrasekhar et al. 2015; Dodd et al. 2016) but was not observed in our survey. However, farm ownership is an inheritance of the land reform in 1947, which redistributed land to poor farmers by restricting the size of landed property (Chandra 2000).

The development of borewells observed in the Berambadi watershed since the 1970s also occurred in other parts of India, especially in other hard-rock aquifer areas such as Madhya Pradesh, were the number of borewells increased by nearly eleven times from 1986-2001 (Bassi 2014). This trend generated a high density of borewells that caused them to interfere with each other (Aubriot 2013). Borewell interference occurs when a borewell's area of influence comes into contact with or overlaps that of a neighboring borewell (Aubriot 2013; Bassi 2014). Borewell interference may be one reason for the high percentage of borewell failures. Borewell failure is often due to failure in identifying the exact water-bearing zones or aquifers, which is common in hard-rock regions in India (Ballukraya and Sakthivadivel 2002; Bassi 2014). Results showed that technological developments increased borewell depth over the past 10 years in the Berambadi watershed. However, a recent study on hard-rock aquifers in Karnataka demonstrated that nearly 70% of all fractures occur within a depth of 100 m, and the probability of encountering fractures decreases considerably below 100 m (Sivaramakrishnan et al. 2015). Aubriot (2013) indicated that farmers' willingness to drill deeper may be linked to social and prestige-related aspects.

The spatialization of the typology was based on the village which is recognized as an important criterion for spatialization to consider for instance the social structure (see panchayat). Other criteria may be interesting for spatialization such as the distances to main roads, the soil properties and the groundwater level at the farm location to discuss the access to markets and crop outlets as well as constraints to crop choices and farming practices. Farm-type locations in the watershed follow an east-west gradient, with more irrigated farms in the east and more rainfed farms in the west (Figure 3.7). This farm-type distribution is linked to the trend in investing in irrigation since the 1990s which caused the unusual inverse gradient of the groundwater table (Sekhar et al. 2006; Javeed et al. 2009).

The typology presented here was based on farming context, farm performances and farming practices. We identified three types of farms: 1) large diversified and productivist farms located mainly in the center of the watershed, 2) small and marginal rainfed farms located in the central and western portions of the watershed, and 3) small irrigable marketing farms located in the eastern portion. This typology is similar to the one generated in Tamil Nadu (Senthilkumar et al. 2009; Senthilkumar et al. 2012) where a first type, including the wealthiest farms with large irrigated land holdings (average = 6 hectares), were distinguished from a second type, including medium wealth with an average land holding of 3 hectares, and from two other types of farms considerably poorer and marginal at meeting their family food requirements based on rainfed crops grown during the monsoon season.

This typology makes it possible to simplify and represent farm diversity across the watershed. The study's results are specific to its purpose and study area. The farm types identified cannot necessarily be extrapolated to a larger context outside the Berambadi watershed. For instance, the farm typology developed in West Bengal (Goswami et al. 2014) differs from ours mainly because of the diversity of farming systems identified there. While we identified five cropping systems based on access to irrigation (irrigated and/or rainfed cropping systems) and crop orientation (cash and/or subsistence cropping systems), they distinguished four farming systems based on the sources of farmers' maximum gross income. These included rice, vegetables, fish and off-farm based farming systems. However, the two-step method combining MCA and AHC is subject to generalization for even larger regions (Kristensen et al. 2004; Milán et al. 2006; Laoubi and Yamao 2009; Goswami et al. 2014).

This study predicts two scenarios for the watershed: 1) farmers, especially on small, irrigated marketing farms and large productivist irrigated farms, may continue to maximize profits by producing high water-demanding crops and cash crops; and 2) irrigation technology may continue to spread toward the western portion of the watershed and convert small rainfed farms into small irrigable marketing farms. Simulation models may help determining whether these scenarios may be sustainable in terms of groundwater depletion and farmers' incomes.

3.6. Conclusion

The typology presented here should enable policy makers to better assess the potential influence of agricultural and water-management policies on farmers' livelihoods and the groundwater table. The typology can be used in simulation models to predict impacts of climate change, specifically higher evapotranspiration, on farming practices and the groundwater level. Such simulation models are useful to test policies aiming to slow groundwater-table depletion and limit income risks due to crop failure. For example, simulation models could explore policies to maintain small rainfed farms (e.g. subsidizing rainfed crops, especially subsistence crops such as pulses) or policies to encourage farmers to adopt better water management in cropping systems, (e.g. decreasing the area of crops that consume large amounts of water, such as banana, sugar cane and turmeric, or modifying electricity availability or subsidizing drip irrigation or less water consuming crops or varieties).

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TABLE CAPTION

Table 3.1. Definition of variables for farming context, farm performance and farming practices used to generate the farm typology

Category	Code	Definition	Class	Abbreviation
Farming context				
Spatial	village	Kuthanur	village 1	V1
		Bheemanabeedu, Mallaianapura	village 2	V2
		Kannagala, Gopalpura, Maddaiana Hundi, Haggadahalli, Hangala Hosahalli, Kallipura, Kunagahalli, Honnegowdanahal, Devarahalli	village 3	V3
		Berambadi, Berambadi Colony, Navilgunda, Kaggalada Hundi, Bechanahalli, Lakkipura	village 4	V4
		Maddur, Maddur Colony, Channamallipura	village 5	V5
Land resource	nbJeminu	number of plots (jeminu) of the farm	1 jeminu	J1
			2 jeminus	J2
			3 jeminus	J3
			>3 jeminus	J3+
	nbPlot2013	number of plots cultivated in 2013	1 plot	P1
			2 plots	P2
			3 plots	P3
			>3 plots	P3+
	totalHHSize	total farm size in hectares	<0.8 hectares	S(--)
			]0.8 hectares;2 hectares]	S(-)
			]2 hectares;4 hectares]	S(+)
			>4 hectares	S(++)
Irrigation resource	isIrrigated	at least one jeminu irrigated	no	rainfed
			yes	irrigated
	nbWorkingBorewell	number of working borewells in 2014	none	W(0)
			1 borewell	W(1)
			>1 borewell	W(1+)
	nbFailedBorewell	number of failed borewells in 2014	none	fail(0)
			1-2 borewells	fail(1-2)
			3 borewells	fail(3)
			>3 borewells	fail(3+)
	hoursKharif	number of hours of electricity per day during kharif in 2014	none	hours(0)
			[2 hours;3 hours]	hours(2-3)
			]3 hours;4 hours]	hours(4)
			]4 hours;8 hours]	hours(4+)
Animal resource	TLU	number of livestock on the farm {oxen, bull, buffalo, cow}=1, {sheep, goat}=0.2	none	TLU(0)
			]0 TLU;2 TLU]	TLU(1-2)
			>2 TLU	TLU(2+)
Farm performances				
Production costs	CostInput2014	cost of farming per hectare during kharif in 2014	[0 Rs-3700 Rs]	C(--)
			]3700 Rs-7400 Rs]	C(-)
			]7400 Rs-14800 Rs]	C(+)
			>14800 Rs	C(++)
Production incomes	IncomeRabi2013	income from selling crops per hectare during rabi in 2013	[0 Rs-18500 Rs]	I(--)
			]18500 Rs-37000 Rs]	I(-)
			]37000 Rs-74000 Rs]	I(+)
			>74000 Rs	I(++)
Farming practices				
Cropping system	CS	type of cropping system in 2014	rainfed, only cash crops	CS1
			rainfed, cash and subsistence crops	CS2
			irrigated, only cash crops	CS3
			irrigated and rainfed, only cash crops	CS4
			irrigated and rainfed, cash and subsistence crops	CS5

Table 3.2. Specificities and homogeneities of the farm types

			TYPE 1		TYPE 2		TYPE 3	
Category	**Code**	**Class**	**Specificity**	**Homogeneity**	**Specificity**	**Homogeneity**	**Specificity**	**Homogeneity**
Farming context								
Spatial	village	V1	7%	5%	1%	0%	**91%**	29%
		V2	4%	5%	28%	16%	**68%**	43%
		V3	36%	**73%**	44%	39%	20%	20%
		V4	15%	13%	**67%**	25%	18%	8%
		V5	6%	3%	**92%**	20%	2%	0%
Land resource	nbJeminu	J1	7%	16%	**62%**	**64%**	31%	37%
		J2	22%	30%	30%	18%	48%	33%
		J3	24%	17%	38%	12%	38%	13%
		J3+	43%	36%	16%	6%	41%	17%
	nbPlot2013	P1	6%	16%	**59%**	**62%**	35%	42%
		P2	19%	20%	36%	17%	46%	25%
		P3	18%	21%	36%	18%	46%	26%
		P3+	**67%**	43%	10%	3%	23%	7%
	totalHHSize	S(--)	4%	7%	**54%**	40%	42%	35%
		S(-)	14%	37%	46%	**52%**	40%	**50%**
		S(+)	44%	39%	23%	9%	33%	14%
		S(++)	**100%**	17%	0%	0%	0%	0%
Irrigation resource	isIrrigated	rainfed	1%	3%	**94%**	**88%**	5%	5%
		irrigated	31%	**97%**	9%	12%	**61%**	**95%**
	nbWorkingBorewell	W(0)	6%	17%	**75%**	**91%**	19%	27%
		W(1)	27%	**56%**	10%	9%	**64%**	**66%**
		W(1+)	**63%**	27%	2%	0%	35%	7%
	nbFailedBorewell	fail(0)	12%	36%	**65%**	**83%**	23%	33%
		fail(1-2)	31%	31%	17%	7%	**52%**	26%
		fail(3)	21%	11%	21%	5%	**59%**	15%
		fail(3+)	26%	22%	13%	5%	**61%**	26%
	hoursKharif	h(0)	3%	8%	**91%**	**90%**	6%	7%
		h(2-3)	15%	22%	7%	4%	**78%**	**57%**
		h(4)	15%	14%	9%	4%	**75%**	34%
		h(4+)	**86%**	**56%**	7%	2%	7%	2%
Animal resource	globalAU	AU(0)	8%	12%	**53%**	33%	39%	28%
		AU(1-2)	18%	33%	40%	32%	43%	39%
		AU(2+)	28%	**55%**	40%	34%	33%	32%
Farm performances								
Production costs	CostInput2014	C(--)	14%	17%	**54%**	28%	32%	18%
		C(-)	19%	34%	46%	36%	34%	30%
		C(+)	21%	31%	39%	26%	40%	30%
		C(++)	20%	17%	29%	11%	**51%**	22%
Production incomes	OutputRabi2013	I(--)	13%	15%	**56%**	27%	30%	17%
		I(-)	16%	23%	**54%**	35%	30%	22%
		I(+)	20%	32%	41%	28%	39%	31%
		I(++)	26%	30%	19%	9%	**54%**	30%
Farming practices								
Cropping system	CS	CS1	1%	2%	**92%**	**65%**	7%	5%
		CS2	3%	2%	**97%**	24%	0%	0%
		CS3	17%	9%	10%	4%	**73%**	38%
		CS4	17%	10%	11%	7%	**72%**	**53%**
		CS5	**87%**	**53%**	1%	0%	12%	3%

Note: Specificity means "x% of the farms with this class belong to this farm type" (columns sum to 100%), while Homogeneity means "x% of the farms belonging to this farm type have this class" (lines sum to 100%).

FIGURE CAPTION

Figure 3.1. Location of the case study. The Berambadi watershed belongs to the South Gundal watershed located in southern Karnataka state. GW is the ground water level below ground (m). The GW level comes from extrapolation of data measured on 600 disused borewells at the end of 2012 monsoon.

Figure 3.2. Spatialization of statistically different farm characteristics on the watershed. Black lines refer to gram panchayat borders, grey lines refer to village borders, green area describes the forest.

Figure 3.3. Distribution of irrigated farms and number of borewells per farm on the watershed. The maps present for the 12 villages 1) the distribution of irrigated farms, 2) the average number of borewells drilled per farm, 3) the average number of working borewells per farm and 4) the average number of failed borewells per farm.

Figure 3.4. A) Projection of the variables used to generate the farm typology in the plane of the first two factors of Multiple Correspondence Analysis (MCA); B) Projection of the class of variables used to generate the farm typology in the plane of the first two factors of the MCA. Variables and class are described in Table 3.1..

Figure 3.5. Dendrogram of individuals from Agglomerative Hierarchical Clustering performed on the first 12 components of the Multiple Correspondence Analysis. Type 1 are large, diversified and productivist farms. Type 2 are small, marginal rainfed farms. Types 3 are small, irrigable marketing farms. Using the first 12 principal components in an AHC algorithm, we obtained a typology with three farm types (red line). Jump in between-cluster inertia is represented in the right corner.

Figure 3.6. Individuals of the three farm types projected on the plane of the first two dimensions of the Multiple Correspondence Analysis. Type 1 are large, diversified and productivist farms. Types 2 are small, marginal rainfed farms. Type 3 are small, irrigable marketing farms.

Figure 3.7. Groundwater table gradient (colors) and farm typology (pie chart) for each of the five villages (V1 to V5) on the Berambadi watershed. Type 1 are large, diversified and productivist farms. Type 2 are small, marginal rainfed farms. Type 3 are small, irrigable marketing farms. Grey lines refer to the borders of the 12 villages, green area describes the forest. The ground water level was obtained using disused borewells and mesured at the end of 2012 monsoon (NB: no borewell was monitored in the forest and close by the forest leading to a partial map of ground water level).

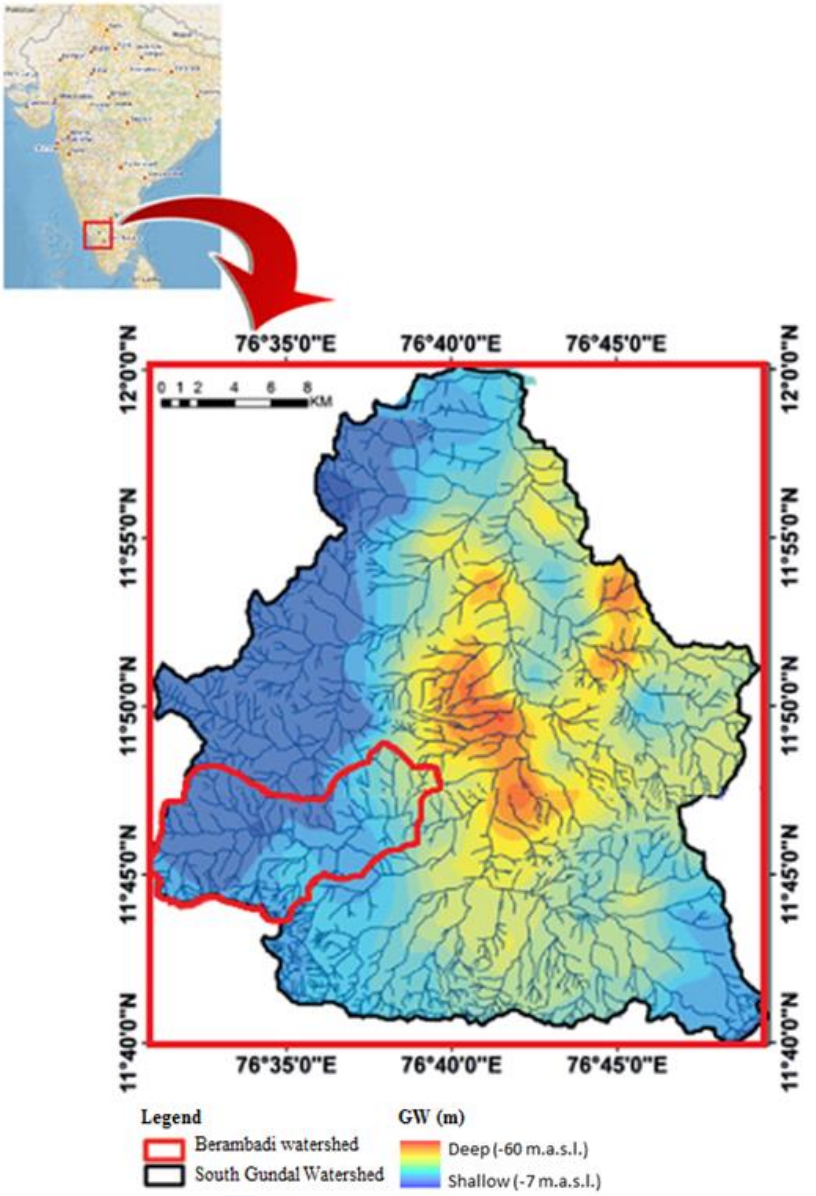
76°35'0"E
76°40'0"E
76°45'0"E
12°0'0"N
11°55'0"N
11°50'0"N
11°45'0"N
11°40'0"N
0 1 2 4 6 8 KM
Legend
Berambadi watershed
South Gundal Watershed
GW (m)
Deep (-60 m.a.s.l.)
Shallow (-7 m.a.s.l.)

Figure 3.1

Figure 3.2

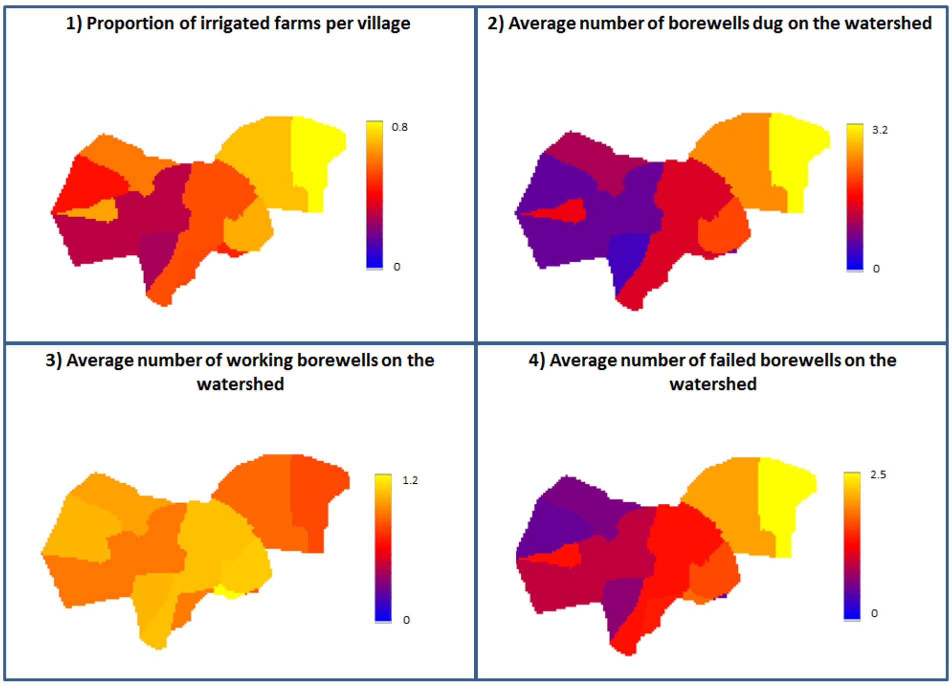

Figure 3.3

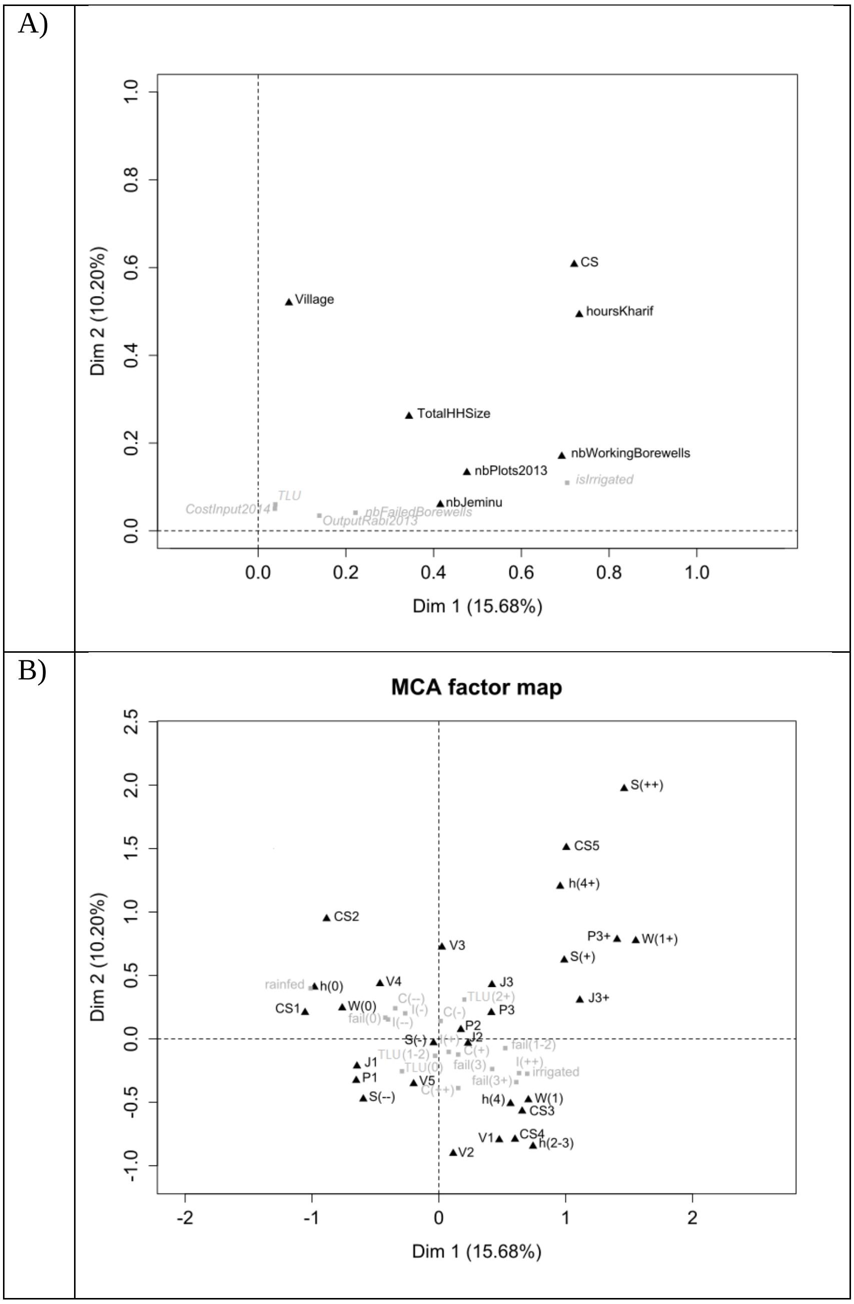
A)
Dim 2 (10.20%)
Dim 1 (15.68%)
CS
Village
hoursKharif
TotalHHSize
nbWorkingBorewells
nbPlots2013
isIrrigated
nbJeminu
TLU
CostInput2014
nbFailedBorewells
OutputRabi2013
B)
MCA factor map

Figure 3.4

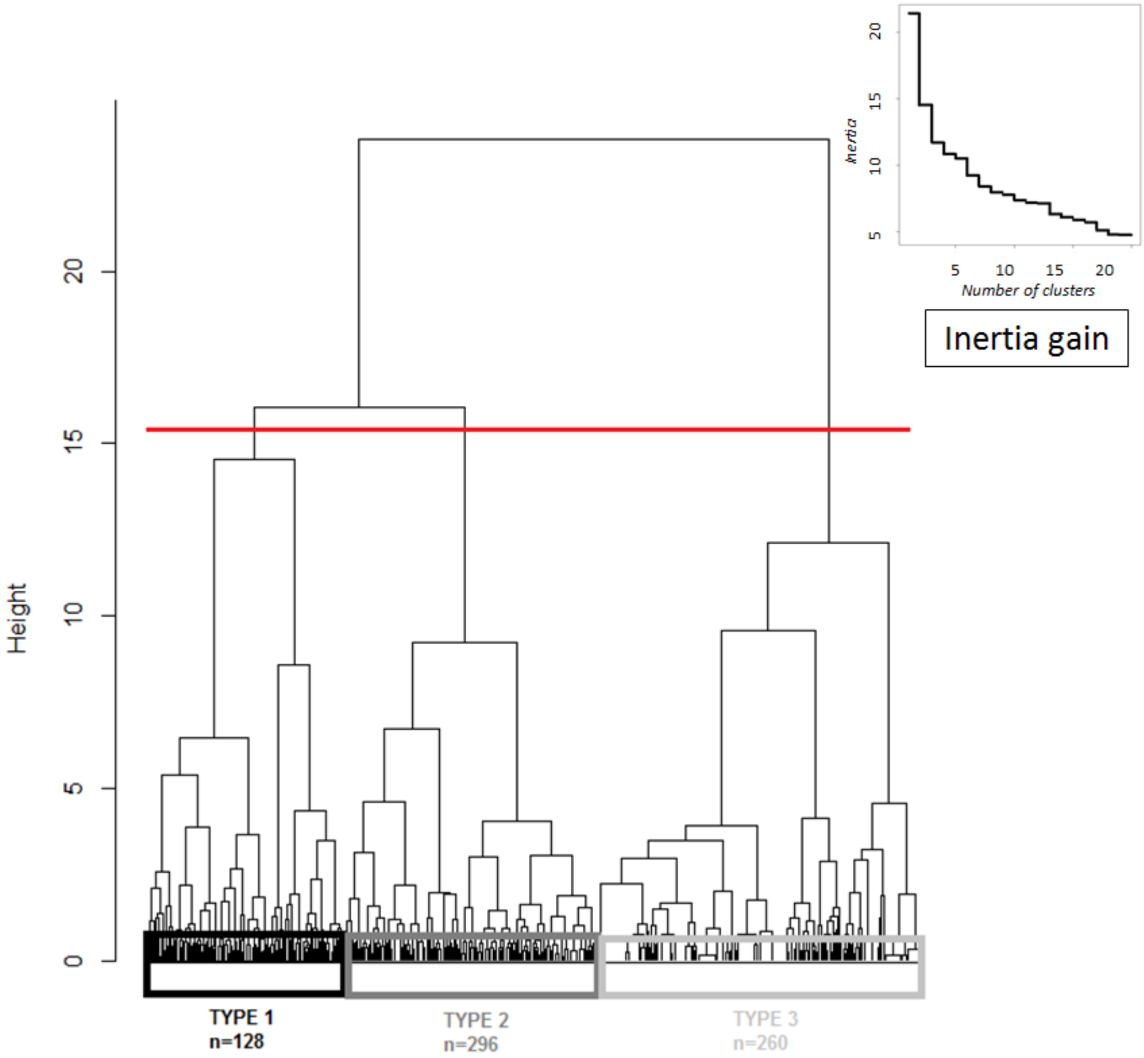
Height
0
5
10
15
20
Inertia
Number of clusters
Inertia gain
TYPE 1
n=128
TYPE 2
n=296
TYPE 3
n=260

Figure 3.5

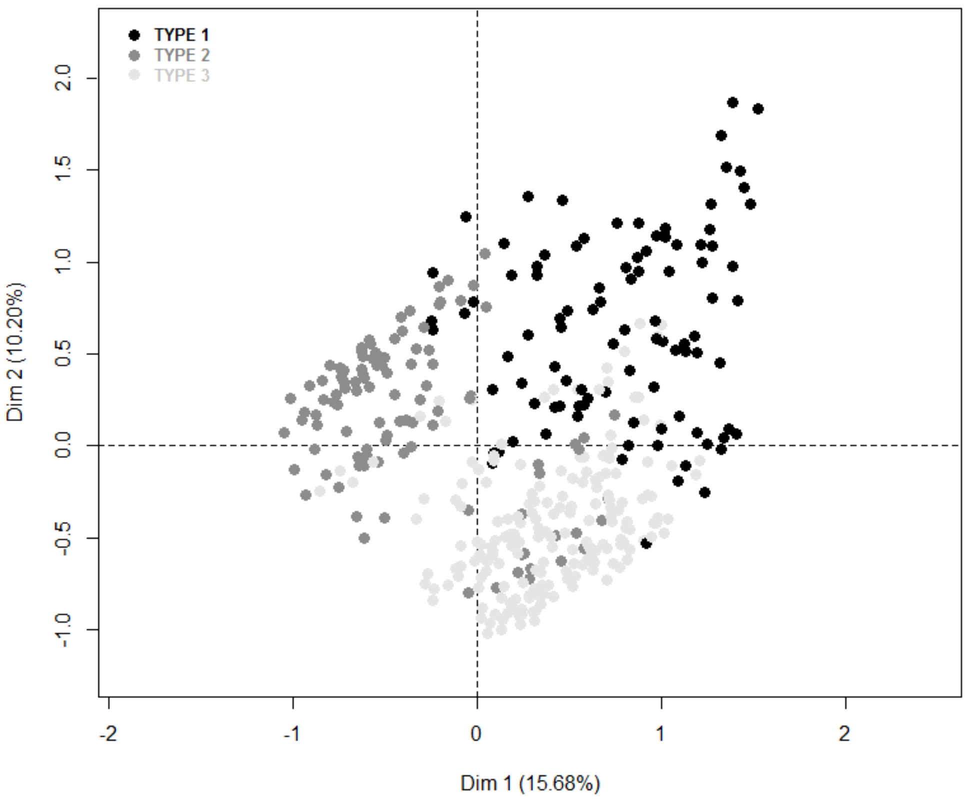

Figure 3.6

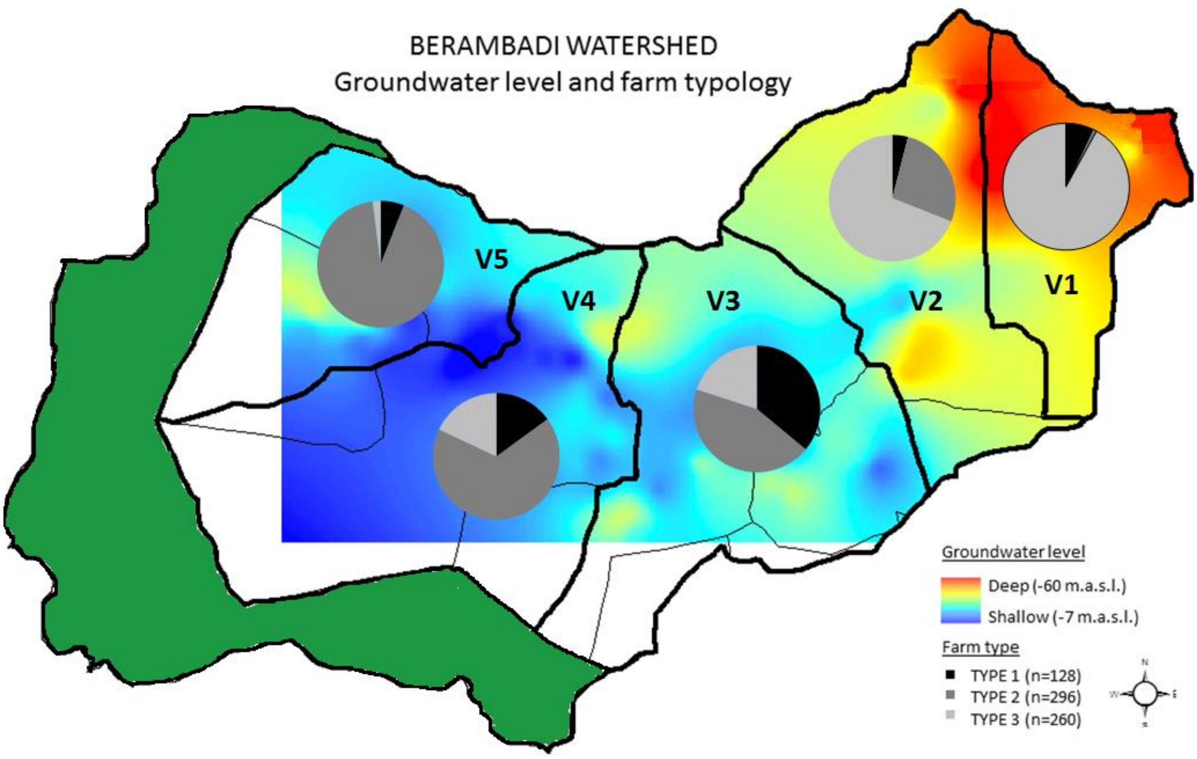

Figure 3.7

Chapter 4

CMFDM: A methodology to guide the design of a conceptual model of farmers' decision-making processes

Marion Robert[1,*], Jérôme Dury[1], Alban Thomas[2], Olivier Therond[1], Muddu Sekhar[3], Shrini Badiger[4], Laurent Ruiz[5] & Jacques-Eric Bergez[1]

[1] AGIR, Université de Toulouse, INPT, INP-PURPAN, INRA, 31320, Castanet Tolosan, France
[2] INRA, Toulouse School of Economics, UMR 1081 LERNA, F-31000 Toulouse, France
[3] IISC, Department of Civil Engineering, Bangalore 560012, India
[4] ATREE, Bangalore 560 064, India
[5] INRA, UMR 1069 SAS, F-35042 Rennes, France

*: Corresponding author, Tel: +33 (0)5 61 28 50 30. E-mail: marion.robert@toulouse.inra.fr

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The agricultural research community offers languages and approaches to model farmers' decision-making processes but does not often clearly detail the steps necessary to build an agent model underlying farmers' decision-making processes. We propose an original and readily applicable methodology for modelers to guide data acquisition and analysis, incorporate expert knowledge, and conceptualize decision-making processes in farming systems using a software engineering language to support the development of the model. We propose a step-by-step approach that combines decision-making analysis with a modeling approach inspired by cognitive sciences and software-development methods. The methodology starts with case-based analysis to study and determine the complexity of decision-making processes and provide tools to obtain a generic and conceptual model of the decisional agent in the studied farming system. A generic farm representation and decision diagrams are obtained from cross-case analysis and are modeled with Unified Modeling Language. We applied the methodology to a research question on water management in an emerging country (India). Our methodology bridges the gap between field observations and the design of the decision model. It is a useful tool to guide modelers in building decision model in farming system.

Keywords: decision modeling, farming systems, water management, case-based analysis, cognitive task analysis, UML

4.1. INTRODUCTION

The agricultural research community has a particular interest in modeling farming systems to simulate opportunities for adaptation that ensure flexibility and resilience of farming systems. To account for actors and their actions in the environment, it is essential to precisely represent their decision-making processes. Some methods have been developed to describe farmers' decision-making processes such as the "model for actions" (Aubry et al. 1998a), rule-based models (Bergez et al. 2006; Donatelli et al. 2006) and activity-based models (Clouaire and Rellier 2009; Martin et al. 2013). However none specifies precisely the process between farmers' decision-making and the modeling activity. In the real world, people do not exhibit optimal behavior like that described in well-structured and controlled experimental settings. One major contribution of the naturalistic decision making (NDM) community is in describing how people make decisions in real-world settings (Klein 2008). NDM starts with field research. NDM asserts that the structure and content of decision-making processes are defined by the organization of the domain in which the decision maker is acting (Zsambok and Klein 2014). It is therefore pointless to develop a decision model without a detailed understanding and formal representation of the relationship between the knowledge farmers have in a specific domain and the decisions they make. Building a conceptual model is a standard step in model development. It describes the model without programming language and facilitates communication between modelers and analysts. However, these conceptual representations are often oriented towards a computerized implementation of the model. Consequently, they do not detail the structure of the system and how it functions (Lamanda et al. 2012).

The objective of our paper is to propose an original and readily applicable methodology to formalize the conceptual modeling of the farmer agent underlying decision-making processes in farming system (CMFDM) and to guide data acquisition and analysis, the incorporation of expert knowledge, and the design of a model. The methodology combines techniques for system description based on field research in natural settings and techniques from the software engineering field regarding the use of software engineering language to support the development of a model. Our research may provide a useful tool for modelers looking for clear guidance on how to build the agent sub-model in a farming system model.

4.2. FOUNDING PRINCIPLES OF THE METHODOLOGY

Our conceptual modeling of farmers' decision-making processes in farming system methodology (CMFDM) is based on three founding principles: 1) Theory building from cases is used to obtain a relevant theory from observing actual practices in a natural setting (Glaser and Strauss 1967; Eisenhardt

1989; Yin 2013). Theory building from case studies is a research process using qualitative and quantitative methods to gather data from one or more case studies in a single natural setting, considering contextual and time aspects of the current phenomenon studied without any experimental control or manipulation (Meredith 1998). The use of case studies is the basis for developing the theoretical constructs and propositions from empirical evidence. Theory is emergent in the sense that it develops from cross-case analysis and the recognition of patterns of relationship within and across cases. Theory building is a recursive cycling process among the case data, the emerging theory and the literature. The first part of the process is inductive going from cases to new theory while the second part of the process is deductive seeking to test the theory previously build with another set of data (Carroll and Swatman 2000; Carlile and Christensen 2005; Eisenhardt and Graebner 2007). The process is totally iterative since it constantly involves backward and forward iterations between case comparison, and theory implementation. Grounded theory research, case researches according to Yin (1994) and Eisenhardt (1989) are well established empirical methodologies for theory building from case (Steenhuis and Bruijn 2006) ; 2) Cognitive-Task Analysis (CTA) is used to analyze and model the cognitive processes that gave rise to farmers' task performance in farming systems (Jonassen 1997; Chipman et al. 2000). CTA provides information about knowledge, cognitive processes, and goal structures needed to solve complex problems and perform tasks (Zsambok and Klein 2014). With the help of CTA, the analyst looks at the system from the perspective of the person performing the task. An important part of the analysis is tracking past critical events that shape a person's feelings or expectations about the task (Schraagen et al. 2000). CTA includes a step to map the different tasks, identify the critical decision points and cluster, link and prioritize them and characterize the strategy used to face them (Klein 1989). CTA has a wide and varied pool of methods among which the most frequently used are structured interviews, verbal protocol analysis ('think-aloud' protocols, retrospective verbal protocols), and critical decision methods (Klein 1989) ; 3) Unified Modelling Language (UML) is used to represent the decision-making problem in a standard and readily usable form for computer programming (Booch et al. 1996; Papajorgji and Pardalos 2006). UML is a standardized object-oriented modeling language in the software engineering field (Booch et al. 1996; Papajorgji and Pardalos 2006).UML is an efficient way to transcribe and abstract information for modeling purposes due to its similarity to knowledge objects (Milton and Kazmierczak 2006). UML has been used as ontology language (Cranefield and Purvis 1999; Pinet et al. 2009). Classes, concepts and relationships are defined and form a common vocabulary for analysts, and modelers who need to share information on the domain (Beck et al. 2010). The ontology is a "formal explicit specification of a shared conceptualization" (Gruber 1993). The visual representation of UML graphs facilitates the design process of the ontology.

Based on these three founding principles, we defined a standardized methodology aiming at guiding the translation of selected case-study observations into a conceptual representation of a generic decision model of the farming system. It is organized into four steps that are combined in an iterative process (Figure 4.1).

4.3. THE CMFDM METHODOLOGY

4.3.1. Step 1: problem definition

The first step is problem definition. Ideally, the theory building from cases research should start without any theory or hypothesis to test under consideration. However, it is truly impossible to reach this ideal but it is important to attempt to approach it in order to avoid bias and limits in the findings because of preordained theoretical perspectives. Thus, the definition of the context and the initial research question is important in theory building from cases to not become overwhelmed by the volume of data. Moreover, a priori framework can be designed to shape the initial design of the theory building research that can potentially specify some important variables identified in the literature but it should be done by avoiding any consideration of relationship between variables or hypothesis.

4.3.2. Step 2: case study selection

The second step is the selection of case studies. As in statistical researches, selecting the population likely to exhibit the research focus is essential to control variations and define the limits of the generalization process. The appropriate population is characterized by satisfying criteria for the research question defined earlier. However the sampling of cases from the appropriate population is particular and is based on a theoretical sampling approach driven by the search for diversity instead of a statistical search for representativeness (Glaser and Strauss 1967; Eisenhardt and Graebner 2007). Case studies may be selected to replicate previous cases, extend the emergent theory, or fill theoretical categories. Random selection is not advised given the limited number of cases studied, but selection of extreme cases or polar types is preferred.

4.3.3. Step 3: data collection and analysis of individual case studies

The third step is data collection and analysis of individual case studies based on CTA and UML. Five sub-steps are followed. First, based on the prior definition of the context, the initial research question and the framework potentially advanced in STEP 1, the analyst is able to shortlist multiple data collection methods and tools that can be both qualitative and quantitative. Tools used are usually interviews, surveys, observations, document analysis and standard quantitative measure like questionnaires. Using multiple data collection method presents two main advantages: 1) it makes possible the triangulation between collected data providing stronger evidences of theory constructs and hypothesis; 2) it overlaps data analysis and allows the analyst to take advantage of flexible data collection and to make adjustment during this process. These adjustments ensures some flexibility and arises new data collection opportunities to probe emergent themes or new theoretical insights in order to understand each individual case as much deep as possible. Secondly, based on the prior definition of the context, the initial research question and the framework potentially advanced in STEP 1, appropriate UML representations for the important variables identified in the literature are selected among the list of UML structural and behavioral diagrams. This step ensures that the representation maps directly to the information reached by a specific data collection method and provides direction and order to identify sub-variables and relationship between variables. Thirdly, data is collected in the field. In one hand, data collection is dedicated to become more familiar with the individual context by identifying specific characteristics of individual environment and the sequence of activities or tasks realized by each individual. This information are obtained from document analysis and direct interaction with the farmer through survey and questionnaire that help identifying farmer's knowledge on the farming context. On the other hand, data collection aims at capturing the cognitive processes set up to realize tasks. In this purpose, critical decision method (Klein, 1989) is used as a knowledge-elicitation method to collect farmer's knowledge and identify critical incidents that disrupt farming management and allow adaptive behavior elicitation. Data collection is emergent in theory building from cases. That means what the analyst learns from the data collected from one individual case often is used to determine subsequent data collection. Fourthly, individual cases are analyzed and verified. An initial transcription using UML representation is made of the information collected and then presented to the concerned farmer for verification, refinement, and revision during a second meeting. This ensures that representation of a task and the underlying cognitive components are sufficiently complete and accurate to format into a formal individual conceptual model. Finally, verified individual conceptual model on farmers' knowledge and cognitive processes are formally represented with UML diagrams. This step allows the unique pattern of each case to emerge before generalizing patterns across cases.

4.3.4. Step 4: the generic conceptual model

The last step is the transition from individual case studies to a generic model. It is an iterative process of cross-cases analysis, enfolding of literature, and incorporation of expert knowledge. One way to do the cross-cases analysis is to list similarities and differences between individual analysis and UML graphs. Another way is by selecting dimensions and to compare cases related to these dimensions. Concepts and relationship between variables emerge from cross-cases analysis shaping hypothesis and theories. It is essential to compare the emergent results from cross-cases analysis with the extant literature in order to improve the theory validity and enlarge its generalizability. Relationship and concepts that are replicated across most or all of the cases or at least validated by the literature are retained to ensure robustness and generalizability. Experts and modelers are also used to strengthen development of the generic model by formulating and adding more complex and meta concepts. It leads to the addition of abstract classes that are not usually used by farmers. In that respect, the generalization of classes is an important process in object oriented modeling (Papajorgji and Pardalos 2006). The generic conceptual model is formatted with the UML graphs and leads to an ontological analysis that formalizes and efficiently specifies concepts and relationships among these concepts.

4.4. METHODOLOGY IMPLEMENTATION IN A CASE STUDY

4.4.1. Step 1: problem definition

We applied the methodology to farming systems in the context of irrigation water management under water scarcity. We chose to focus the application of our methodology on the conceptual representation of a farmer. 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, cognitive agents have been commonly represented as Belief-Desire-Intention (BDI) agents (Bratman 1987b; Rao and Georgeff 1991). The concept of Belief represents the farmer's knowledge of the system. Desires are the objectives or satisfying goals of the farmer. Intentions are actions plan to achieve the farmer's objectives (Desires). The BDI framework is founded on the well-known theory of rational action in humans. BDI agents are considered as having an incomplete view of their environment. We used the BDI to structure the formal knowledge produced by the CMFDM. Our conceptual representation of a farmer included the knowledge on the farm structure and on the decision-making processes and adaptations. Contrary to normative approaches, BDI is a practical reasoning representation used to simulate bounded rationality and is an intuitive representation of the human decision-making process. Compared to fully rational approaches, its descriptive capacity enables the representation of decision processes that are the closest to reality. To provide the BDI structure, we agree with Rider (2012) that cognitive task analysis is an efficient transition between farmers' decision processes in the real world and its representation.

4.4.2. Step 2: case study selection

CMFDM was applied, inter alia, on water management of small farm holders in an emerging country (India). In the Berambadi watershed (Karnataka state, southern India), farmers are facing increasing temperatures, unpredictable rainfall, and groundwater depletion. Agriculture depends greatly on rainfall and access to irrigation. While groundwater access is nearly free and limited only by the availability of electricity, many farmers encounter dry and temporarily non-functioning borewells. Water table levels display a non-standard pattern, hydrogeologically speaking; valley regions have deeper groundwater levels than topographically higher zones. Thus an unusual groundwater level gradient is observed with shallow water in the upstream and deep water in the downstream. Farms are really small, less than one hectare, with mainly manual and animal traction work capacity. Farms are composed of jeminus (plots) subdivided into beles (crop plots) that change from year to year. The cropping system is organized around three seasons: i) the rainy season, when most of the crop is grown (kharif); ii) the winter season, when mainly irrigated crops are grown (rabi); and iii) the dry season, when little cultivation occurs (summer). Monsoon rainfall is a key determinant for crop choice. Crops may be under contract, directly sold to agents or markets, or are for subsistence. Farmers are highly in debt due to investing in irrigation systems. Government subsidies greatly reduce the price of chemical fertilizers and provide affordable inputs. The methodology was used to identify farmers' knowledge and crop management decisions in a context of changes in rainfall and groundwater level. The main concern was to understand and model the adaptation processes of the farmers who face these changes. The population was local crop farmers on the watershed. The farmer population is characterized by the following criteria: location, farm size, and access to irrigation. We interviewed 27 farmers from 10 villages spread across the Berambadi watershed selected to have farms from all over the watershed in area where the water table is really deep or really shallow and in transitional zone. We selected very big farms as well as very small farms that could be irrigated or rainfed.

4.4.3. Step 3: data collection and analysis of individual case studies

Firstly we shortlisted the data collection methods and tools to use for our case study in India. Document analysis on farming context on the watershed, at the state level or at the country level was important to get familiar with the Indian field prior to the survey stage. We reviewed the literature on crop management practices, irrigation practices, water issues, water management, and market and climate trends in Karnataka. We met with extension service agents and researchers to gather general and specific information about the watershed. The survey process was based on a questionnaire to frame the interview process and to get quantitative measures shared by all survey done. We constructed a questionnaire based on the three parts of the BDI: 1) the farmers' beliefs (farm structures and characteristics), It focused on household characteristics, the farm structure, assets, and partnerships, In-depth questions were asked about irrigation, borewells, and rainfall; 2) the farmers' desires (objectives and cropping pattern). We asked farmers about their objectives and crop production over the past three years. Since no records were kept from year to year, information about historical management went no further than three years in the past; 3) the farmers' intentions (decisions and adaptations). It aimed to reveal the farmers' actions, reactions and adaptations to different events. We questioned farmers about how they foresee their cropping-plan and asked them to describe the sequence of decisions concerning cropping-plan decisions made the year before sowing. At this stage, farmers usually describe a general decision plan for optimum conditions. Comparing this plan to the past cropping system showed that crops actually grown can differ from the given cropping system. We encouraged farmers to point out events that make them change their cropping system. To depict farmers' practices and support the cognitive elicitation process, we used a timeline chart on which the farmers placed stickers to represent farm activities and decision timing. The farmers indicated when specific events occurred and explained what was done to address them. The survey process also combines extensive maps and direct observations. Cadastral maps and district maps were used to mediate the farm data collection process at the watershed scale. We realized direct observation and took notes on physical farm characteristics like plot organization, building and borewell locations, distance to roads, etc. After details about household organization, farm assets, and farm marketing position, we asked farmers about their objectives and crop production over the past three years. We mediated this step by extensive use of farm maps.

Secondly, we selected UML representations for the collected data. Structural diagram are appropriate to represent the static aspect of the system. We used object diagrams for the representation of the farm structure. Behavioral diagrams basically capture the dynamic aspect of a system. We used activity diagrams to represent the decision-making processes, sequence diagrams to represent the interaction and flow of information exchanged between the diverse entities of the farming system, use case diagram to represent the relationships among the functionalities and their internal/external actors like farmers' partnership, relationships with sellers and buyers.

Thirdly, data was collected in the field. A preliminary test of the questionnaire showed that farmers were not responsive to open-ended questions. Since interviewers were not researchers or farmers, we limited open-ended questions with multiple-choice questions that included ranking preferences. Specific terms for agronomic concepts such as "crop sequence", "crop rotation", and "previous-crop effect" were avoided and addressed using examples. We avoided controversial questions about potential costs and water or electricity fees. Beyond the questionnaire, the survey data collection process was adapted to each farmer depending on previous interviews, on farmer's answer, and on observations made. Thus questions were added to look deeper into some farmer's answers or to react to field observations. For instance, when unexpected crops were mentioned while asking for the crops grown in 2012, 2013 and 2014, the interviewer asked for complementary explanation to justify the farmer's crops choice made during these years. Also the interviewer added references to other interviews while talking to the farmer to ask the farmer's opinion on why he is behaving differently. For instance he asked why a certain farmer was not growing any sunflower when most of the other farmers interviewed are.

Fourthly, we build an initial transcription of the knowledge collected and returned to ask farmers to verify, refine, confirm and revise our preliminary results and emerging rules. This helped to introduce actions that are obvious to farmers, such as growing sorghum depending on family grain stocks and not officially including it in a crop rotation.

Finally, individual conceptual model on farmers' knowledge and cognitive processes are formally represented with UML diagrams. To illustrate individual conceptual models, we focus in this part on 1) the representation and structure of the knowledge of the farmer with object diagrams; 2) the representation of the decision-making processes with activity diagrams.

1) The farmer described the farm as a structure using four or five types of resources: land, labor, equipment, livestock and, water (for irrigated farms). To illustrate the method, we focus on farmland representation. We constructed individual object diagrams that depict farmers' representation of their farmland organization. Two examples include:

- For Indian farmer In1 (Figure 4.2A), land organization differed between seasons in a fully rainfed system. The number and size of plots changed from kharif to rabi due to high dependency on rainfall in winter. Part of the land was more fertile due to application of tank-bed silt two years previously. The farmer preferred to grow cash crops on the fertile land and subsistence crops on the less-fertile part.
- For Indian farmer In2, farmland (20 acres) was divided into two jeminus (Figure 4.2B). The management differed on each jeminu. One was irrigated, and the other was fully rainfed. He grew cash crops on the irrigated jeminu and preferred subsistence crops on the rainfed one. His land organization during rabi was less sensitive to rainfall since water from a borewell enabled crop growth during that season.

2) Concerning the decision-making processes of farmers, our analysis revealed that drought and water restrictions, market prices, access to contracts, and delay in rainfall or monsoons in India were critical incidents that push farmers to adapt. We asked them to explicitly describe alternative decisions that are made when these changes occur. We identified two typical adaptation phases. At the beginning of the season before any crop operations occur, farmers observe changes in the environment that lead them to

adapt some or all of the cropping system. After starting land preparation, the farmer may change a crop at the plot scale. Le Gal et al. (2011) and Risbey et al. (1999) described the first level of intra-annual decisions as "tactical" and daily decisions as "operational". We offer an example on an Indian farmer:

- Indian farmer In2 adapted his cropping system based on borewell yield, sunflower market prices, and sorghum family grain stocks (Figure 4.3). During kharif, he set the irrigated area for long-term crops (turmeric) and short-term crops (garlic) based on observing his borewell and estimating how much water it would provide. In the case of a deep water table, the farmer replaced crops having high water requirements with cash crops having low water requirements. In rainfed conditions, sunflower price and sorghum family grain stocks influenced the area planted in sunflower. For rabi, the farmer decided to cultivate or fallow his land based on borewell yield and expected rainfall.

4.4.4. Step 4: the generic conceptual model

For the Indian case study, we built a generic decision model. We compared individual analysis and graphs to each other, referred to the literature, and asked experts and modelers to participate in the model development.

We selected the following dimensions to highlight patterns in terms of similarities or differences between cases: irrigation access, farm size, number of jeminu, village, and cash crop production. At this stage, irrigation access clearly shows differences in land managements between fully rainfed farms and irrigable farms. Kharif is the main cropping season to cultivate in the watershed. We focused on kharif cropping systems to identify similarities between farms. Rainfed farmers are small to marginal farms going from 0.12 hectares to 2 hectares. We observed two behaviors: growing only crop to sell or growing also subsistence crops. Cross-case in the irrigable farms highlights three types of farms: farms fully irrigated and growing only cash crops, farms growing cash crops in irrigated and rainfed conditions, and farms growing cash and subsistence crops in irrigated and rainfed conditions.

Concerning the representation of farm structure knowledge, the individual analysis from step 3 highlights concepts used by farmers to organize their land and define their cropping system (Figure 4.4). Concepts mentioned by most or all the Indian farmers were "season", "soil fertility", "jeminu", "crop type", "irrigability" and "bele" (see farmers In1 and In2). One also talked about "ownership" saying he had different practices on owned land and on rented land and another about "temporary plot" by having a jeminu located in the Berambadi tank that is usable only when the water level in the tank is low enough. We did not retain the last two concepts that were not relevant for the other farmers. We complemented the bottom-up incorporation from farmers with top-down incorporation from experts and modelers. Modelers and experts used abstract classes to summarize concepts. We generalized the concepts "*Season", "Soil", "Jeminu"*, into *TemporalUnit*, *BiophysicalUnit, and PhysicalUnit,* respectively. The "bele" is considered as the *ManagementUnit where crop practices are effective.* "Irrigability" and "crop type" were included with the *ManagementUnit*. Farmers can develop several cropping systems with different crop management practices, which we called *CropManagementBlock*.

Concerning the representation of decision-making processes and adaptation, we aim at getting generic decision frame for each group; we crossed individual tactic decision UML activity diagrams (Figure 4.3) to build a generic model (Figure 4.5). For instance, we focus on Indian farmers growing cash and self-consumption crops under irrigated and rainfed conditions.

All farmers mentioned borewell yield as the primary factor that could change their cropping system and cause them to reassess their irrigable area and long-term and short-term irrigated crops. Market prices and available water for irrigation may influence their crop choice at the beginning of each season. Management of the rainfed land depends on sorghum and finger millet stocks, and prices. Half of the farmers also mentioned that the farm location from a local market or a main road influenced their crop choice. They explained that they have higher chance to get contracts on beetroots or cabbages when their farm is along a main road. Half of them also considered marigold contracts offered by marigold the cropping season which ensure minimum revenue. An important part of farmers also mentioned rainfall expectations or monsoon expectation as a condition for selecting rainfed crops. Deep root crops are favored when rainfalls are expected to be low. Two farmers mentioned religious festivals as a motivation for growing watermelon and one mentioned possible swaps of subsistence crops with his neighbor to justify not selecting sorghum crop. We did not retain the last two concepts that were not relevant for the other farmers. We complemented the bottom-up incorporation from farmers with top-down incorporation from experts and modelers. Irrigated crops are classified in either long-term (11-month to three-year) and high water- demanding crops (turmeric, sugar cane and banana), short-term crops (less than 11 months) with high water requirements (garlic and onion), or short-term crops with low water requirements (watermelon, beetroot, cabbage and other vegetables) (Figure 4.5). Rainfed crops are for selling (sunflower, marigold, horse gram, and groundnut) or for subsistence (sorghum and finger millet). The generic decision frame of Indian farmers growing cash and self-consumption crops under irrigated and rainfed conditions (Figure 4.5) consider first the borewell yield to estimate the proportion of irrigated and rainfed land. Then for the irrigated plots, water is distributed to the different crop types identified by the experts and modelers. Farm location and market prices are the next levels to select irrigated crops. Concerning rainfed crops, grain stock status determines whether the farmer will grow subsistence crops. Then marigold contracts and market prices control the rainfed crop choice. Farmers look at crop prices proposed by marigold companies while selecting their rainfed crops which is the only crops with prices fixed at the beginning of season.

The methodology also provided generic plans for crop-management decisions and adaptations at sowing and germination times to allow farmers to adapt in case of the inability to sow or low germination.

4.5. Discussion - Conclusion

The agricultural research community has a particular interest in decision-making processes design in farming systems but does not have a clear framework to guide it in how to proceed from field studies to designing the conceptual model. We identified a gap between field observations and the design of a conceptual decision model by modelers. In this article, we provided a necessary, original, and useful step-by-step methodology that guides data acquisition and analysis, incorporation of farmers' knowledge, and model design. Developing a methodology for model design was necessary to ensure model transparency. It is essential to include information about the process followed to develop the conceptual or simulation model. This helps reproduce the work so that future researches can test any insights found or replicate the process in another study.

We offered an original methodology that combines several widely used frameworks to elicit and represent a cognitive agent behaving in interaction with its environment to go toward computer modeling. Our methodology belongs to the range of qualitative methodologies that aim at understanding a particular phenomenon from the perspective of those experiencing it (Ryan and Bernard 2000). Similarly to the ethnographic decision modeling, our methodology aims at studying behavior and practices in a natural setting using triangulation of the multiple data collection approaches. However, the step-by-step methodology proposed by Gladwin (1989) aims to not generate theories from cases but to understand farmers' behavior from a cultural perspective in terms of patterns of learned and shared behavior and beliefs of a particular social, ethnic, or age group. Thus in ethnographic decision modeling focus is usually made on one particular aspect of the reality setting rather than the whole context.

The case-study approach enables building a conceptual model with a higher level of refinement than statistical methods. Statistical studies combine dissimilar cases to obtain a large sample and run the risk of conceptual stretching (George and Bennett 2005), whereas case studies can reach a high level of validity with a smaller number of cases. Case studies help to obtain a relevant theory from observing actual practices. In fully understanding the nature and complexity of the decision-making process, it helps to answer the *why* rather than just the *what* and *how*. Combining both a bottom-up (from farmers) and a top-down (from experts and modelers) approach is a pragmatic way to develop consistent and reusable models based on shared concepts (Milton and Shadbolt 1999; Beck et al. 2010). The sampling of case studies is an important step in the methodology; the diversity criteria must be supported by existing literature. The intervention of external experts during the generalization process is also an important methodological element to prevent an overflow of too many case-specific details. CTA enables farmers to express their knowledge in its most natural and intuitive form – their spoken language (Rider 2012). However, the use of knowledge-acquisition techniques to elicit farmers' representations is not straightforward and is time-consuming (Hoffman and Lintern 2006). The need for direct observations and the use of multiple methods and tools add difficulties to the methodology. The selection of cases is essential to the approach but can lead to selection bias. The researcher must not select cases that promote a favored hypothesis or exclude cases that conflict with initial theories.

To model farmers and their perspective of the world it is important to consider farmers' representation of their environment, their objectives and their intentions and decisions to achieve the desire state. Both farmers' knowledge and decisions have to be modeled within a generic decision models.

Unlike ethnographic decision modeling that predicts behavioral choices under specific circumstances displayed in decision trees (Gladwin 1989; Ryan and Bernard 2006), decision tables (Mathews and Hill 1990) or a set of rules in the form of *if-then* statements (Ryan and Martinez 1996), our methodology considers also farmers' knowledge and representation using a unique and formal language. Like Becu et al. (2003), we argue that the use of the formal language UML is an effective way to transcribe and abstract information for modeling purposes because of the similarity between knowledge objects and UML methods (Milton and Shadbolt 1999). We could have used other tools since UML was not initially used for ontology development, like the ontology web language (Lacy 2005). However, UML has a rapidly growing community with strong support and has already been successfully tested for ontology building (Kogut et al. 2002). We used UML as a unique formal language that facilitates iterations and feedback between different methodological steps. It also ensures consistency and transparency during the process from knowledge transcription to decision-model application. We used UML instead of cognitive maps (Mackenzie et al. 2006; Voinov and Bousquet 2010) or decision trees for knowledge and dynamic decision representation because UML represents the decision-making problem in a standard and readily usable form for computer programming. It enables efficient programming and data storage while limiting distortions between the conceptual and computer models due to programming constraints (Papajorgji and Pardalos 2006).

This methodology was successfully used to design a conceptual model for the simulation model CRASH (Crop Rotation and Allocation Simulator using Heuristics) to plan, simulate and analyze cropping-plan decision- making at the farm scale in France (Dury 2011) and the decision model NAMASTE (Numerical

Assessments with Models of Agricultural Systems integrating Techniques and Economics), which simulates Indian farmers' decision-making processes at tactical and operational levels (Robert et al. 2015; Robert et al. (Under Review)).

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FIGURE CAPTION

Figure 4.1: The four methodological steps to conceptualize a farming systems and to guide data acquisition and analysis, integration of expert knowledge, and computer implementation.

Figure 4.2: Farmland organization described with a Unified Modelling Language (UML) object diagram: (A) Indian farmer in the northeast of the Berambadi watershed: cropping-system allocation depends on the season and soil type; (B) Indian farmer in the middle of the Berambadi watershed: cropping-system allocation depends on the jeminu (plot), irrigation equipment, and the season.

Figure 4.3: Decision rules described with a Unified Modelling Language (UML) activity diagram for an Indian farmer in the middle of the Berambadi watershed: the farmer adapts his cropping system depending on borewell yield, sunflower market prices, and sorghum family grain stocks.

Figure 4.4: Generic Farmland organization using a Unified Modelling Language (UML) class diagram. Rectangles with thin borders represent concepts from the bottom-up integration. Rectangles with thick borders represent abstract classes from the top-down approach.

Figure 4.5: Generic decision framework for Indian farmers growing cash and subsistence crops in irrigated and rainfed conditions during the kharif season described with Unified Modelling Language (UML) activity diagrams. Farmers adapt their crops at the beginning of the season depending on market prices, rainfall, access to contracts, and family grain stocks.

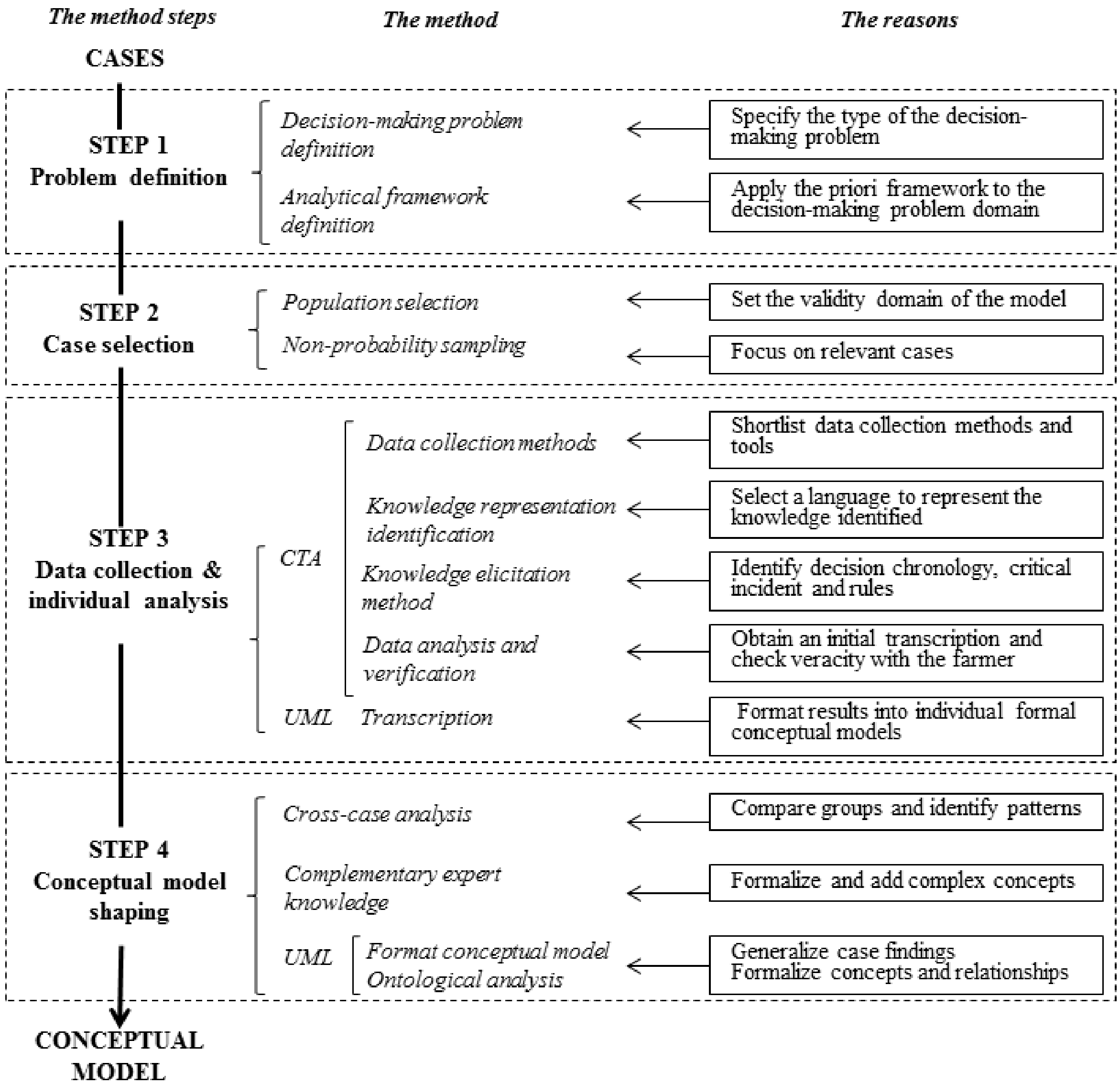

The method steps
The method
The reasons
CASES
STEP 1
Problem definition
Decision-making problem definition
Analytical framework definition
Specify the type of the decision-making problem
Apply the priori framework to the decision-making problem domain
STEP 2
Case selection
Population selection
Non-probability sampling
Set the validity domain of the model
Focus on relevant cases
STEP 3
Data collection & individual analysis
CTA
Data collection methods
Knowledge representation identification
Knowledge elicitation method
Data analysis and verification
UML
Transcription
Shortlist data collection methods and tools
Select a language to represent the knowledge identified
Identify decision chronology, critical incident and rules
Obtain an initial transcription and check veracity with the farmer
Format results into individual formal conceptual models
STEP 4
Conceptual model shaping
Cross-case analysis
Complementary expert knowledge
UML
Format conceptual model
Ontological analysis
Compare groups and identify patterns
Formalize and add complex concepts
Generalize case findings
Formalize concepts and relationships
CONCEPTUAL MODEL

Figure 4.1

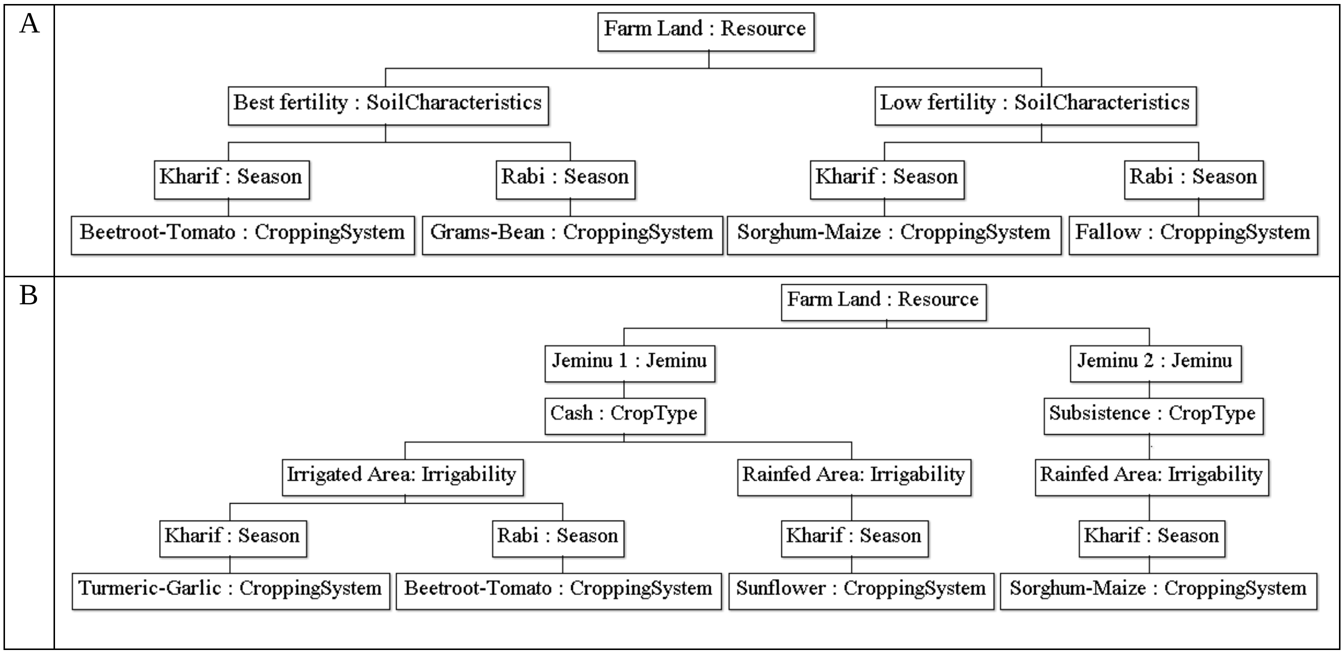

A
Farm Land : Resource
Best fertility : SoilCharacteristics
Low fertility : SoilCharacteristics
Kharif : Season
Rabi : Season
Kharif : Season
Rabi : Season
Beetroot-Tomato : CroppingSystem
Grams-Bean : CroppingSystem
Sorghum-Maize : CroppingSystem
Fallow : CroppingSystem
B
Farm Land : Resource
Jeminu 1 : Jeminu
Jeminu 2 : Jeminu
Cash : CropType
Subsistence : CropType
Irrigated Area: Irrigability
Rainfed Area: Irrigability
Rainfed Area: Irrigability
Kharif : Season
Rabi : Season
Kharif : Season
Kharif : Season
Turmeric-Garlic : CroppingSystem
Beetroot-Tomato : CroppingSystem
Sunflower : CroppingSystem
Sorghum-Maize : CroppingSystem

Figure 4.2

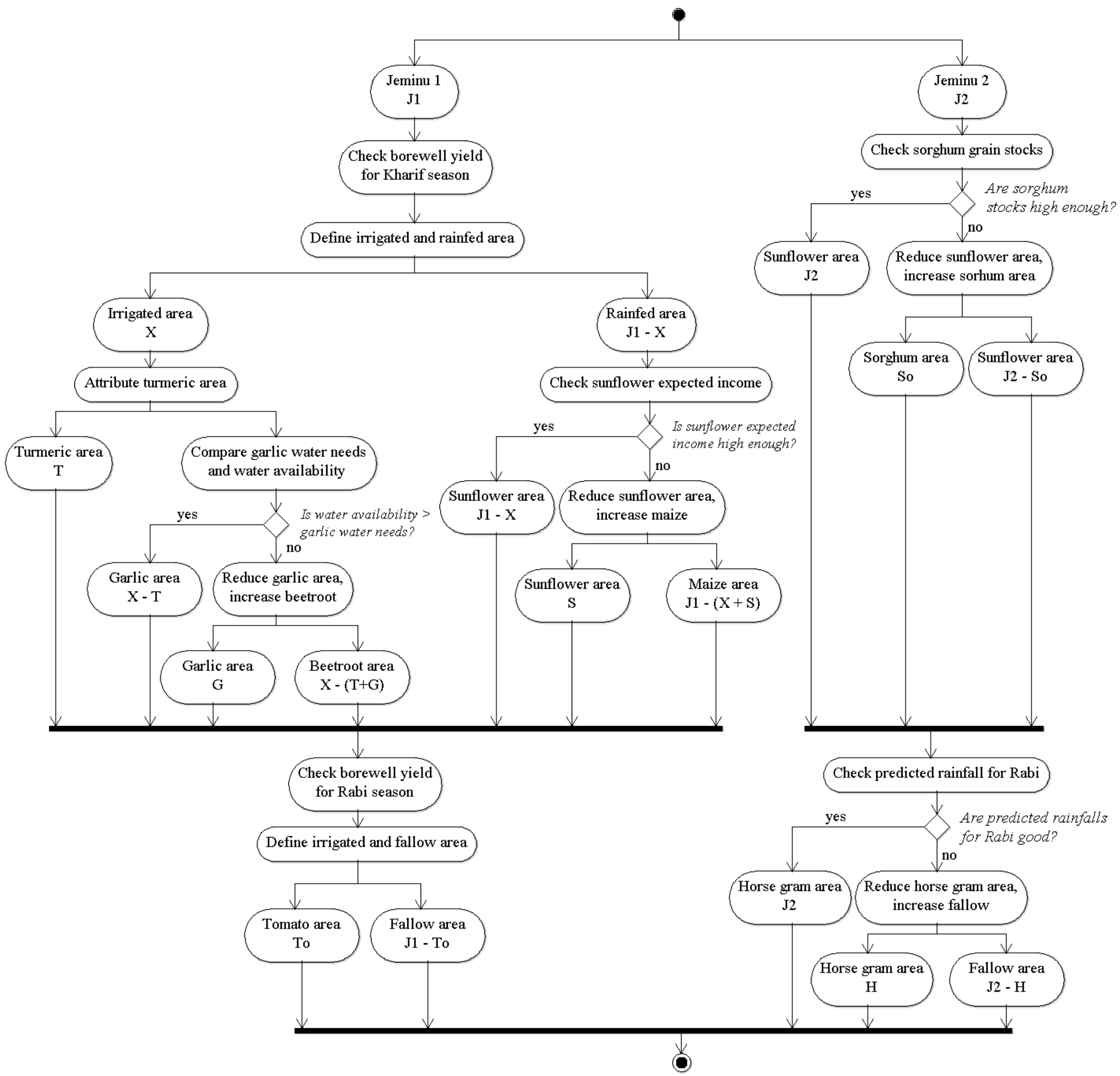

Jeminu 1
J1
Jeminu 2
J2
Check borewell yield
for Kharif season
Define irrigated and rainfed area
Irrigated area
X
Rainfed area
J1 - X
Attribute turmeric area
Turmeric area
T
Compare garlic water needs
and water availability
yes
Is water availability >
garlic water needs?
no
Garlic area
X - T
Reduce garlic area,
increase beetroot
Garlic area
G
Beetroot area
X - (T+G)
Check sunflower expected income
yes
Is sunflower expected
income high enough?
no
Sunflower area
J1 - X
Reduce sunflower area,
increase maize
Sunflower area
S
Maize area
J1 - (X + S)
Check sorghum grain stocks
yes
Are sorghum
stocks high enough?
no
Sunflower area
J2
Reduce sunflower area,
increase sorhum area
Sorghum area
So
Sunflower area
J2 - So
Check borewell yield
for Rabi season
Define irrigated and fallow area
Tomato area
To
Fallow area
J1 - To
Check predicted rainfall for Rabi
yes
Are predicted rainfalls
for Rabi good?
no
Horse gram area
J2
Reduce horse gram area,
increase fallow
Horse gram area
H
Fallow area
J2 - H

Figure 4.3

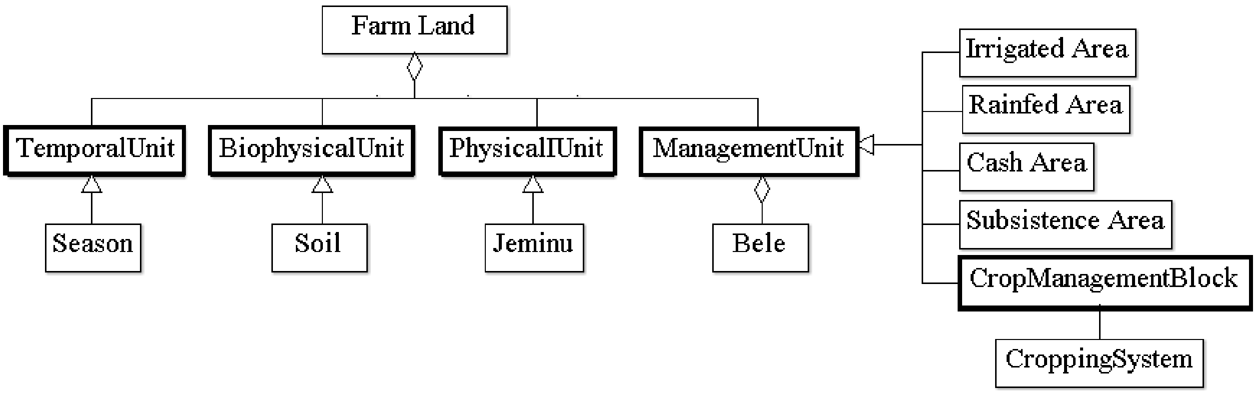
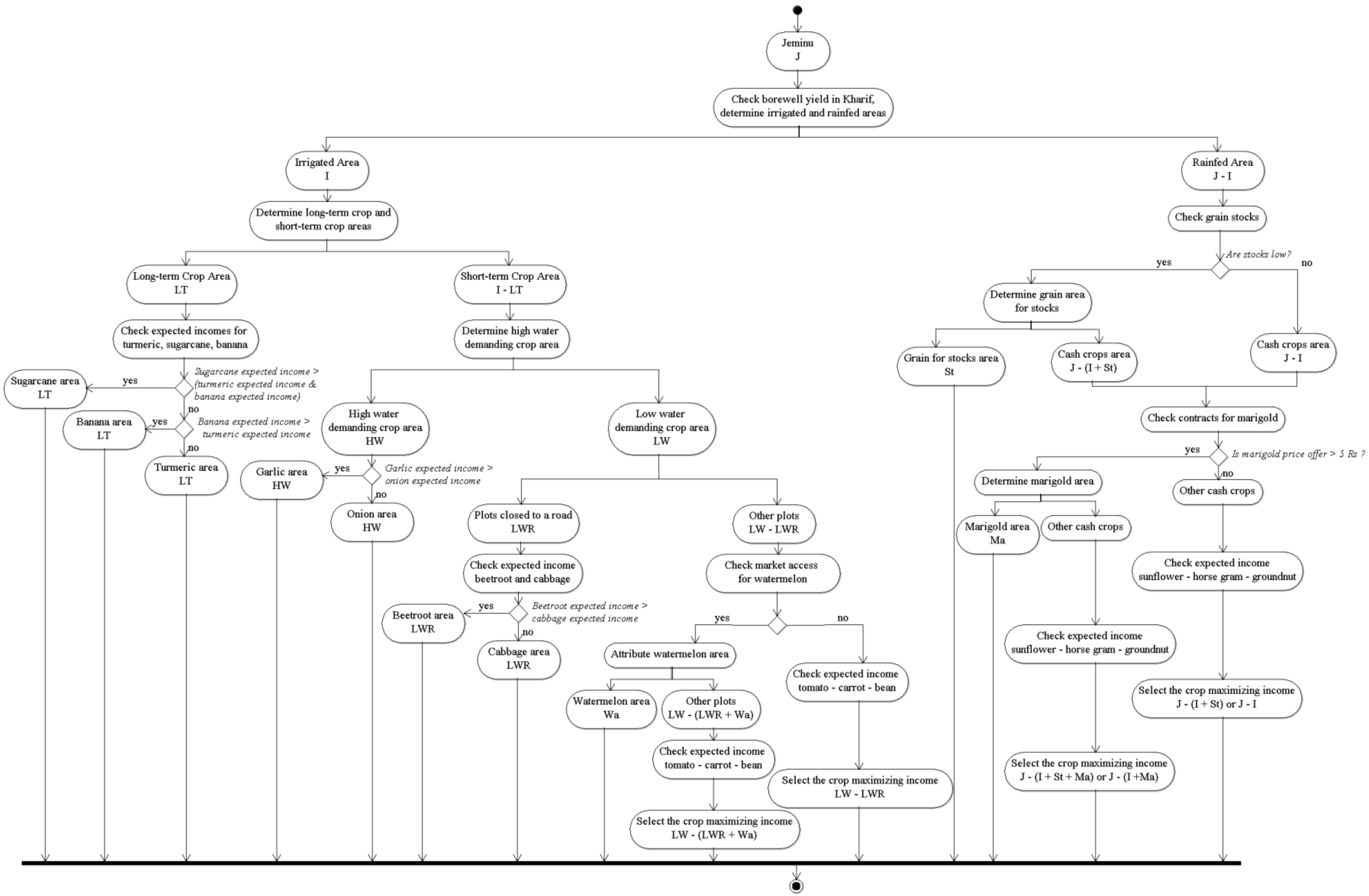

Farm Land
TemporalUnit
BiophysicalUnit
PhysicalIUnit
ManagementUnit
Season
Soil
Jeminu
Bele
Irrigated Area
Rainfed Area
Cash Area
Subsistence Area
CropManagementBlock
CroppingSystem

Figure 4.4



Jeminu J
Check borewell yield in Kharif, determine irrigated and rainfed areas
Irrigated Area I
Rainfed Area J - I
Determine long-term crop and short-term crop areas
Check grain stocks
Are stocks low?
yes
no
Long-term Crop Area LT
Short-term Crop Area I - LT
Determine grain area for stocks
Check expected incomes for turmeric, sugarcane, banana
Determine high water demanding crop area
Grain for stocks area St
Cash crops area J - (I + St)
Cash crops area J - I
Sugarcane expected income > (turmeric expected income & banana expected income)
Sugarcane area LT
Banana expected income > turmeric expected income
Banana area LT
Turmeric area LT
High water demanding crop area HW
Low water demanding crop area LW
Check contracts for marigold
Is marigold price offer > 5 Rs ?
Garlic expected income > onion expected income
Garlic area HW
Onion area HW
Determine marigold area
Other cash crops
Plots closed to a road LWR
Other plots LW - LWR
Marigold area Ma
Check expected income beetroot and cabbage
Check market access for watermelon
Check expected income sunflower - horse gram - groundnut
Beetroot expected income > cabbage expected income
Beetroot area LWR
Cabbage area LWR
Attribute watermelon area
Check expected income tomato - carrot - bean
Watermelon area Wa
Other plots LW - (LWR + Wa)
Select the crop maximizing income J - (I + St) or J - I
Select the crop maximizing income LW - LWR
Select the crop maximizing income J - (I + St + Ma) or J - (I +Ma)
Select the crop maximizing income LW - (LWR + Wa)

Figure 4.5

Chapter 5

Adaptive and dynamic decision-making processes: A conceptual model of production systems on Indian farms

Marion Robert*[1], Alban Thomas[2], Muddu Sekhar[3,7], Shrinivas Badiger[4], Laurent Ruiz[5,7], Hélène Raynal[6]and Jacques-Eric Bergez[1]

[1]AGIR, Université de Toulouse, INPT, INP-PURPAN, INRA, 31320, Castanet-Tolosan, France

[2]INRA, Toulouse School of Economics, UMR 1081 LERNA, F-31000 Toulouse, France

[3]Indian Institute of Sciences, Department of Civil Engineering, Bangalore 560012, India

[4]ATREE, Bangalore 560 064, India

[5]INRA, UMR 1069 SAS, F-35042 Rennes, France

[6]INRA, UR 0875 MIAT, F-31326 Castanet-Tolosan, France

[7]Indo-French Cell of Water Sciences, IRD-IISc, Bangalore, India

* Corresponding author: (marion.robert@toulouse.inra.fr)

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Farming systems are complex structures with several dimensions interacting in a dynamic and continuous manner around farmers' management strategies. This complexity peaks in semi-arid regions of India, where small farms encounter a highly competitive environment for markets and resources, especially unreliable access to water from rainfall and irrigation. To represent such strategies, we propose the conceptual model NAMASTE, which was conceived and based on data collected in the Berambadi watershed in southern India. The most relevant and novel aspects of NAMASTE are i) the system-based representation of farm production systems, ii) the description of dynamic processes through management flexibility and adaptation, and iii) the representation of steps in farmers' decision-making processes at various temporal and spatial scales. Since NAMASTE was designed in an extreme case of highly vulnerable agriculture, its generic framework and formalisms can be used to conceptually represent many other farm production systems.

Keywords: conceptual model, farmer decision-making process, system-based representation, adaptation, irrigation.

5.1. INTRODUCTION

Modeling farming systems and how these systems change and adapt to external changes and opportunities is particularly interesting for the agricultural research community to better assess their flexibility and resiliency. A variety of conceptual representations have been developed to represent decision-making processes with diverse levels of complexity in the system (plot to farm) and the adaptation process (from days to years). Examples include the “model for actions” at the cropping system level and mainly for tactical adaptation (Cerf and Sebillotte 1988; Aubry et al. 1998a), rule-based models (Bergez et al. 2006; Moore et al. 2014; Snow et al. 2014; Holzworth et al. 2015) and activity-based models (Clouaire and Rellier 2009; Martin et al. 2013).

Farmers’ decision-making processes, planned at three different temporal and spatial scales, are a combination of decision stages: i) the strategic decision stage, with a long-term effect (years to decades) on whole-farm organization (e.g., decisions about equipment investment, infrastructure development or farm expansion); ii) the tactical decision stage, with a medium-term effect (several months or seasons) on the farm cropping system and its resource management; and iii) the operational decision stage, with a short-term effect restricted to specific plots and describing daily adjustments to crop management practices (Risbey et al. 1999; Le Gal et al. 2011). Some models focus on one particular type of decision – mainly strategic (Barbier and Bergeron 1999; Berge and Ittersum 2000; Hyytiäinen et al. 2011) or operational (Martin-Clouaire and Rellier 2006; Merot et al. 2008; Martin et al. 2011a; Aurbacher et al. 2013; Moore et al. 2014). Others model two decision levels – strategic and tactical (Trebeck and Hardaker 1972; Adesina 1991; Mosnier et al. 2009) or strategic and operational (Navarrete and Bail 2007; Dury 2011; Taillandier et al. 2012a; Gaudou and Sibertin-Blanc 2013). However, to the best of our knowledge, the scientific literature does not offer models that include a decision model with the three decision stages within the same model. To understand the ability and possibility to adapt farming systems, it is essential to consider the entire decision-making process. Ignoring one decision stage can bias evaluation of the impact of changes on a farm production system and miss possible options for farming system adaptation.

In semi-arid regions, agricultural production systems depend greatly on irrigation and encounter increasing challenges: growing uncertainty about how to respond to climate change, severe depletion of natural resources, high volatility in market prices, rise in energy costs, and greater pressure from public regulations (agricultural, environmental, and health policies). In the Deccan Plateau in India, the development of submersible pump technology in the 1990s resulted in a dramatic increase in borewell irrigation (Sekhar et al. 2006; Javeed et al. 2009). However, the low productivity of the aquifer (Dewandel et al. 2010; Perrin et al. 2011) and a rapid decline in the water table level led to decreasing borewell yields (Ruiz et al. 2015), which means that groundwater-irrigated agriculture still largely depends on rainfall. Climate variability has increased over the last 50 years in this region

(Jogesh and Dubash 2014). Predictions indicate a 1.8-2.2 °C increase in temperature by 2030, and southwestern regions of Karnataka are projected to suffer from a decrease in annual rainfall, especially during the monsoon season (Jogesh and Dubash 2014). For a region that largely depends on monsoon patterns and winter months to maintain agricultural production, any shift in climatic conditions would have a severe impact on natural resources and the economy. This highly complex and competitive environment requires farmers to continuously adapt their farming system and management practices (Hardaker 2004), and it is a place where explicitly considering the three stages of farmer decisions is critical to accurately represent production systems.

The objective of this article is to introduce the conceptual model NAMASTE (Numerical Assessments with Models of Agricultural Systems integrating Techniques and Economics) and detail the explicit integration of the three decision stages: strategic, tactical and operational. A conceptual model is a non-software description of a computer simulation model. It is the bridge between the real system and a computer model (Robinson 2008) and therefore requires simplification and abstraction (Robinson 2010). NAMASTE is well suited to agricultural systems in semi-arid regions highly dependent on irrigation. One original feature of our model is the decision sub-model that covers three stages of decisions and adaptations. Another original feature is the integrated dynamic interaction of different sub-systems that build the farm production system. We first present the methodology used to build the conceptual model. Then, we outline the decision sub-system and its interactions with the biophysical sub-system and the external system. We discuss the key modeling choices and present several insights on how to move from the conceptual model to a computer simulation model.

5.2. MODELING PROCESSES

5.2.1. Indian case study

The design of the conceptual model was based on data collected in the Berambadi watershed (11°43'00” to 11°48'00" N, 76° 31'00" to 76° 40'00" E) in southern India, where biophysical variables have been intensively monitored since 2009 under the Environmental Research Observatory ORE BVET. Since 2013, the multi-disciplinary Indo-French project CEFIPRA (Centre for the Promotion of Advanced Research) AICHA (Adaptation of Irrigated Agriculture to Climate Change) has aimed to develop an integrated model to simulate interactions between agriculture, hydrology and economics and to evaluate scenarios of the evolution of climate, agricultural systems and water management policies at the watershed scale. The Berambadi watershed (84 km²) belongs to the Kabini River basin, which is part of the South Gundal River basin (816 km²) (southwest of Karnataka). Its climate is dominated by a monsoon regime that generates a strong rainfall gradient with decadal trends, strong inter-annual variability and recurrent droughts (Ruiz et al. 2015). Three seasons regulate the farm cropping system: i) kharif (June to September), the rainy season (monsoon), when most of the cropping area is cultivated; ii) rabi (October to January), the winter season, when most irrigated plots are cultivated; and iii) summer (February to May), the hot and dry season, when only few plots are cultivated.

On average, farm size in the Berambadi watershed is 3.6 acres. 47% of the household on the watershed have water access for irrigation. In kharif, crops mainly grown in rainfed condition are sorghum, maize, sunflower, marigold, and in irrigated conditions are turmeric, onion, garlic, and banana. 20% of the cropping area is dedicated to subsistence crops such as sorghum, millet and pulses. In rabi, mainly maize, horse gram and vegetables are grown in irrigated conditions. In summer almost 90% of the crop land is fallow land.

The hard rock aquifer is composed of fissured granite underlain by a 5-20 m layer of weathered material. Hydraulic conductivity and borewell yields decrease with water table depth. As a consequence, continuous pumping leads to groundwater table drawback and reduces the availability of groundwater for irrigation. This feedback makes predefined land-use scenarios unrealistic, since farmers need to adapt their actions continually according to groundwater availability. In addition, water table levels display a non-standard pattern, hydrogeologically speaking; valley regions have deeper groundwater levels than topographically higher zones (Figure 5.2). This pattern results from intensive groundwater pumping since the early 1990s in villages located in the valley (Sekhar et al. 2011) that disconnected groundwater from streams, which now run dry most of the year. Low costs of pumping water and subsidies for irrigation equipment encouraged farmers to drill even more borewells. This dramatic evolution is closely linked to the spatial distribution of soil type and groundwater availability, as well as farming practices, access to the market, knowledge, new technologies and government aid (Sekhar et al. 2011). An increasing number of farmers report well failures and give two reasons for this: either wells have run dry after excessive pumping, or no water was found in newly drilled borewells (González Botero and Bertran Salinas 2013).

The NAMASTE model aims at simulating farmers' adaptation to climate change, water table depletion, economic context and agrarian changes such as government subsidies. Its hierarchical structure is described in Figure 5.1.

5.2.2. Modeling steps

To build the conceptual model we followed a three-step method:

Step 1: We identified events, concepts and knowledge that are relevant to the conceptual model. Knowledge acquisition helps to understand and describe the real system. We surveyed farmers in the watershed in 2014 and 2015. The first survey targeted 27 farmers to obtain detailed data about their practices, in particular their decisions and the process of adapting their decisions. The second survey targeted 680 farmers and obtained broad data about farm characteristics and social, economic and agronomic environment. This survey led to a typology of farmers on the watershed based on biophysical factors (e.g. farm location, soil type, ground water accessibility), on economic factors (e.g. farm size, labor, equipment), on social factors (e.g. castes, family structure, education, off-farm job) (details are found in Robert et al. (in Prep.)). We surveyed seed retailers and Panchayats (village leaders) to learn about recommended crop management practices and village organization. Additionally, 52 experimental plots were monitored over three years, which provided observed quantitative data about crop production and crop management. These data helped supplement the verbal information provided by farmers during surveys. Meteorological data were obtained from a meteorological station and water gauges installed on the watershed. Prices and costs were obtained from farmers and from official district data from the Indian Ministry of Agriculture and Cooperation (Directorate of Economics and Statistics) and the National Informatics Center (Agricultural Census Division).

Step 2: We used the case study CMFDM method (standing for Conceptual Modeling of the Farmer agent underlying Decision-Making processes) (Robert et al. 2016a) to identify system components and the interactions between them that structure and organize farming processes in a coherent systemic representation. CMFDM underpins the development of a conceptual model by combining both a bottom-up from empirical data by observing actual practices in a natural setting and a top-down from experts and modelers. It uses multiple data collection which makes possible the triangulation between collected data providing stronger evidences of theory constructs and hypothesis. Case study method provides a deep understanding of the complex processes used in decision-making processes. Two main systems were identified: i) a farming system, which is complex and composed of interacting or interdependent sub-systems (mainly, decision and biophysical sub-systems), themselves made up of interacting and interdependent entities; and ii) an external system, which is a set of independent entities that describe uncertain and uncontrolled events that influence the production process.

Step 3: We selected the formalisms and frameworks to simulate the target processes. To facilitate the design and coding of the computer model that follows the conceptual model, selected formalisms and frameworks were implemented in the French National Institute of Agronomy (INRA) RECORD (Renovation and COORDination of agro-ecosystem modeling) modeling and simulation software platform within a multidisciplinary approach (e.g. agronomy, soil science, bioclimatology, epidemiology, management science, statistics, applied mathematics and computer science) (Bergez et al. 2013).

The first framework described the systemic representation of the farm production system (Figure 5.3). The production system is divided into three interactive sub-systems: i) the decision sub-system (manager or agent), which describes the farmer's decision process as a combination of knowledge about the system, objectives, and decisions; ii) the operating sub-system (technical system), which translates the decision orders into action execution and dynamics of farm resources; and, iii) the biophysical sub-system, which describes interactions between physical and biological elements, in particular the relations between ground water, soil, and plant growth and development (Clouaire and Rellier 2009; Le Gal et al. 2010; Dury 2011; Akplogan 2013). The farming system interacts with an external system that simulates pressure and conditions in the farming environment such as rainfall (WEATHER) and market prices (MARKET), and specifically in an Indian context, such as electricity service (ELECTRICITY) and the village source of labor and equipment (VILLAGE).

The second framework aimed to organize the decision sub-system (Figure 5.3). We considered farmers as cognitive agents able to think, memorize, analyze, predict and learn to face future events and plan their actions (Le Bars et al. 2005). In artificial intelligence and cognitive sciences, cognitive agents are commonly represented as Belief-Desire-Intention (BDI) agents (Bratman 1987a; Rao and Georgeff 1991). “Belief” represents the agent’s knowledge of the system. We considered that farmers have three types of knowledge (Beliefs). The first two are structural knowledge, concerning farm structure, its organization and its characteristic resources (e.g., land, labor, equipment, and water), and procedural knowledge, concerning farmers’ know-how about farming. With experience, farmers have a basis for deciding and planning their actions. In our approach, procedural knowledge corresponds to the plan library of Georgeff’s Procedural Reasoning System (Rao and Georgeff 1991). The third type is observed knowledge, describing the data that farmers obtain by observing and monitoring changes in the farming environment (e.g., field observations, market monitoring, weather predictions, opportunities to hire labor and rent equipment). “Desires” represents the farmer’s objectives or satisfying goals. The 27 interviewed Indian farmers of the first survey asserted they manage their farms to maximize profits and improve their financial situation by selling cash crops. Optimizing crop production can encourage farmers to improve or invest in irrigation systems. They face a delicate tradeoff among investing in a borewell, adopting new technologies to increase income with a more productive cropping system, accumulating debts, and risking system failures. “Intentions” represents the farmer’s plans for actions to achieve objectives (Desires) by knowing the status of the system (Beliefs). “Intentions” are the decisions farmers must make at strategic, tactical and operational stages.

5.2.3. Conceptual validation

Conceptual validation is essential to ensure that the assumptions, theories and simplifications used to build the conceptual model are sufficiently accurate and relevant to to meet the stakeholders’ requirements and the objectives of the study (Costal et al. 1996; Borenstein 1998; Liu et al. 2011). To validate the conceptual model, we used: i) face validation that consists in asking experts and individuals knowledgeable about the study objectives to evaluate the conceptual model and determine whether it is correct and reasonable for the study purpose; and ii) traces techniques that consists in tracking of entities through each sub-model and the overall model to determine whether the model's logic and the necessary accuracy maintained (Robinson 2010; Sargent 2010; Robinson 2014). Conceptual validation is inherently an informal process referring to subjective and human judgement.

Each sub-model and the overall model must be evaluated to determine if they are reasonable and correct. First, we applied White-Box validation to the sub-models to determine whether each constituent part of the conceptual model represents the real world with sufficient accuracy to meet the study objectives (Robinson 2014). Each sub-system was validated by experts in the associated research field. Experts and modelers were essential for building the decision sub-model. Modelers ensure that decision processes are appropriately designed into the chosen framework and formalisms. Indian agronomic researchers validated the decision rules for crop management and adaption. We also asked Indian researchers from the research project to participate to the validation of each sub-model as main stakeholders on the project and to certify the representation and data used to build the external system.

Second, we applied Black-Box validation to the overall model to determine whether the model provide a sufficiently accurate representation of the real world for the intended purpose of the study (Robinson 2014). The entire system was validated by experts on the different sub-systems, modelers and the Indian researchers. They worked on the consistency between inputs and outputs of each sub-system to ensure rational interactions between systems. Specifications of each sub-model were circulated among those who have a detailed knowledge of the system. They shared feedbacks on whether the model was appropriate by determining if the appropriate detail and aggregate relationships were used for the model's intended purpose.

Finally, information-technology engineers from the RECORD platform verified the feasibility of the model for future computer implementation. Once the conceptual model will be implemented under the modeling and simulation RECORD platform, the validation of the conceptual model will also be expanded with model simulation validation technique.

5.3. A CONCEPTUAL MODEL OF PRODUCTION SYSTEMS ON INDIAN FARMS

5.3.1. What should be modeled

Three major decisions to represent

We identified three major technical decisions that need to be represented in the model.

Type 1: Investing in access to irrigation is essential to expect increase farm irrigation capacity and improve farm productivity. However, it is expensive, and farmers must consider if it is worth becoming indebted to increase their income from irrigated cash crops. Hence, it is a crucial decision that would impact the entire farm production system in the long term.

Type 2: The choice of crops and the design of the cropping system are major decisions in crop farming. Crop rotations are usually defined in the long-term but can be adapted once information about weather and prices becomes more accurate.

Type 3: The realization of crop management operations depends on major decisions on cropping practices, timing and adaptation. Adjusting the timing of crop operations and the amount of inputs are key mechanisms for farmers when adapting to unpredicted weather events and labor and equipment availability. In addition, at our study site, it is not uncommon for farmers, to ensure a minimum income, to decide to destroy a failed crop after a few weeks and sow a shorter-cycle crop, as soon as enough time remains within the season. Resource-use conflicts between operations force the farmer to make daily decisions about the type, timing and location of operations.

Three temporal dimensions of decision-making processes to represent

Farmers make decisions at different stages of the decision-making process.

Stage 1: The strategic decision stage is the moment when farmers make a decision at the beginning of the year that will have a long-term effect on organization of the entire farm for the next 15-20 years. During this stage, farmers decide whether to invest in irrigation equipment to optimize their profit. They also select the corresponding cropping system and associated crop management operations (e.g. land preparation, sowing, fertilization, irrigation, harvest) that will ensure the best income for their long-term climatic and price expectations. For practical reasons we fixed the beginning of the year at the 1st of January.

Stage 2: The tactical decision stage is the moment when farmers make a decision at the beginning of each cropping season (1st of June in kharif, 1st of October in rabi and 1st of February in summer) that will have a medium-term effect on the entire season. This stage establishes the cropping system adopted for the season. Farmers integrate new observed knowledge about climate and prices so that the cropping system initially selected in the strategic stage may no longer best optimize their income. They review their crop selection and match the best practices to obtain the best cropping system for the known farming conditions.

Stage 3: The operational decision stage covers the entire season at a daily time step. From the cropping system selected in the tactical stage, farmers decide and adjust their daily crop operations in each plot depending on climate conditions and resource constraints.

In NAMASTE, information is exchanged between systems as follows (Figure 5.3):

1) At the beginning of the year (1st of January), farmers review their expectations by observing the trends in rainfall, prices and groundwater level. Information is forwarded from the external system to the decisional part of the agent through the operating system. Farmers update their observed knowledge and select the best investment to meet their objectives.
2) At the beginning of the kharif season, farmers search for recent information about rainfall, market prices and groundwater level. Farmers obtain more accurate forecasts of rainfall[3] than the general trend for the monsoon provided at the beginning of the year. Farmers also monitor market prices and borewell yield before a crop season begins. An expectation of higher crop prices or irrigation water availability helps them decide whether they will favor high market-value crops (e.g. cash crops) or high water-demand crops (e.g. long-term crops such as turmeric, banana, and sugarcane). The decision to adapt their cropping systems is based not only on maximizing profit but also on social, economic, and environmental constraints. Their decisions may depend on their farm structure (e.g. equipment type, plot organization, farm size), their resources (e.g. access to irrigation, water-resource diversification), their farm geographic features (e.g. village; proximity to forest, roads, and markets) and their social characteristics (e.g. castes, family structure, education, off-farm job). Once again they update their observed knowledge and review the list of crops to grow for each plot (bele) for the given season.
3) Farmers check the rainfall and groundwater daily to decide when to start an operation (e.g. land preparation, sowing, fertilization, and irrigation). They manage labor and equipment resource allocation between plots via the operating system. Some labor comes from members of the household who work full- or part-time on the farm. However, most are hired from the village. Farmers have to check that enough labor is available in the village for each operation. Some farmers have their own tractor and bulls and are not constrained by this resource for land preparation; others must rent a tractor and/or the bulls to prepare the land. Like for labor, they depend on the availability of equipment at the village level. Based on their updated observed knowledge, they decide and send an operation to the operating sub-system. The operating system interacts with the crop and soil system to perform the action. The crop system returns updates on crop growth and soil characteristics to the operating sub-system. Observations of operation success or failure allow farmers to proceed or not toward the next

[3] The India Meteorological Department and private weather forecasting companies provide seasonal forecasts on their websites at national and regional scales.

operation and re-initiate the observation-update-action-execution-crop loop. The water pumped daily and the phenomena of recharge and percolation are transferred to the groundwater system.

4) At the beginning of the rabi season, the model re-runs the tactical decision processes. Once crops are selected, the operational decision processes lead to crop operations from land preparation to harvest. At the beginning of the summer season, the model re-runs the tactical decision processes, followed by the operational decision processes when it is decided to grow crops.

The entire process is repeated the following year (i.e. strategic, tactical, and operational kharif; tactical and operational rabi; and tactical and operational summer).

5.3.2. Modeling in NAMASTE

Three formalisms to describe the three decisions

1) Formalism 1: Stochastic dynamic programming formalism for the investment decision

We developed an economic model to represent the decision about irrigation equipment and to simulate cropping system adaption after the investment (details are found in Robert, Bergez, et al. (in Prep.). To simplify the notation (Table 5.1), we present the formalism for a single, representative farmer so that the only indexes used are for time periods (year indexed by t, season indexed by τ). Each year t, $t= 1, 2,\ldots,T$, farmers must decide whether to invest in irrigation equipment. Investment I_t can include redrilling an existing borewell to have a higher water column so that irrigation lasts longer without changing pumping yield, drilling a new borewell to have an additional source of water for irrigation and increase pumping yield, or purchasing a new pump to increase pumping capacity. Investment in irrigation is an additional component of the existing irrigation capital stock which, in the extreme case of non-irrigation, can be zero. The unit cost of investment in irrigation at year t, denoted r_{It}, corresponds to the interest rate on loans for investment. Investing in a borewell takes time and is costly, which implies that farmers obtain loans, and we assume that only one investment is possible each year. We make the simplifying assumption that investment only occurs at the beginning of the year, i.e., 1st of January

Farmers optimize their decisions over a long time period and consider the consequences of today's decisions about investment in irrigation on future water availability, denoted $\overline{W}_t$, and cropping systems. Farms have a set of plots (bele) indexed by b, $b = 1, 2, \ldots, B$. Crop failure is common due to difficult cropping conditions (e.g. drought, delayed monsoon, animal damage). To account for crop failure, we divided agricultural seasons into six sub-seasons, two per main season: $\tau = k_1, k_2, r_1, r_2, s_1, s_2$. A crop c, c=1, 2, …, C can be irrigated and/or rainfed, grown in kharif and/or rabi and/or summer, which generates several management plans (see section 3 entitled “Formalism 3: Graph of activities for crop management decisions”), on operational decisions). Crop selection is highly influenced by the farmers’ expectations for rainfall and water available for irrigation. Farmers preview and organize their irrigated area. The irrigable area depends on the type of crops grown. Borewell water is distributed to irrigated crops. Irrigated crops are long-term crops (11-month to three-year crops such as turmeric, banana, sugar cane) or short-term crops (less than 11 months). Long-term crops are high water- demanding crops. Short-term crops may (onion, garlic) or may not be (cabbage, beetroot, other vegetables) high water-demanding. Rainfed crops are for selling (sunflower, marigold, watermelon) or for subsistence (sorghum, finger millet, pulses). Field evidence from the 27 interviews and the 52 experimental plots indicates that priority is given to long-term crops, then to high-water-demanding short-term crops and finally to other irrigated short-term crops.

Available water volume for farmer $\overline{W}_\tau$ and season τ depends on several technical features, including daily electricity distribution (hours per day), depth of the well, water pump horsepower, and water table level. $\overline{W}_\tau$ is provided by the model pump from the biophysical sub-system of the farm. $C_{W\tau}$ denotes unit cost of water (excluding possible loan repayments) at time τ. Older irrigation equipment is more prone to failure and to need repairs and is likely to lose efficiency over time. Consequently, we expect total available water $\overline{W}_t$ to decline over time if capital remains unchanged.

Choice of investment is a long-term decision based on farmer’s expectations for rainfall, prices, and seasonal water table changes. Expectations for rainfall and the water table are considered qualitative expectations, indexed by a. Farmers expect a season’s rainfall and groundwater level to be either poor, below average, average, above average, or good. We represented qualitative expectations with a discrete distribution:

$$E_{t-1}(\widetilde{R_\tau}) = \frac{1}{A}\sum_{a=1}^{A}\theta_{a\tau}\,\widetilde{R_{a\tau}} \text{ and } E_{t-1}(\widetilde{GW_\tau}) = \frac{1}{A}\sum_{a=1}^{A}\varphi_{a\tau}\,\widetilde{GW_{a\tau}}$$

where $\theta_{a\tau}$ is the subjective probability of the discrete realization of the climate event $\widetilde{R_{a\tau}}$, and $\varphi_{a\tau}$ is the subjective probability of the discrete realization of the groundwater level event $\widetilde{GW_{a\tau}}$. Concerning the farmer’s expectations for future crop prices, we assumed they are based on past market prices $P_{c,t-1}$ at year *t-1* on crop *c*, such as myopic expectations for prices:

$$E_{t-1}(\widetilde{P_{c,t}}) = P_{c,t-1}.$$

The farmer’s strategic decision is fully dynamic because today’s decision about investment will influence water availability in future periods and thus the crop choice. The dynamic model is written straightforwardly as a stochastic dynamic programming problem by considering that W_t is an observed state variable, and that investment I_t, crop choice *c* and the proportion of available water $PW_{b\tau}$ to each plot *b* are control (discrete and continuous) variables.

The farmer’s strategic decision is written:

$\max_{I_t} E_{\tilde{R}}\, E_{\widetilde{GW}} E_{\tilde{P}} \sum_{t=1}^{T}(1+r)^{-t}\left\{\max_{\delta_{bc\tau}}\left[\sum_{\tau=k_1}^{S_2}\sum_{b=1}^{B}\sum_{c=1}^{C}\delta_{bc\tau}\pi_{cb\tau}\right]-r_{It}I_t\right\},$

where r is a known discount rate,

$\pi_{bc\tau}=\left[\boldsymbol{\theta}_{\widetilde{P_{c,\tau}}}\widetilde{P_{c,\tau}} * \boldsymbol{\theta}_{\boldsymbol{y_{cb\tau}}} y_{cb\tau}\left(\widetilde{R_\tau}, W_{bc\tau}, X_{cb\tau}\right) - r_{X_{cb\tau}}\boldsymbol{\theta}_{\boldsymbol{X_{bc\tau}}} X_{bc\tau} - C_{W\tau}W_{bc\tau}\right],$

Such that

$$\sum_{b=1}^{B}\sum_{c=1}^{C}\delta_{bc\tau}W_{bc\tau} \leq \bar{W}_\tau, \qquad \forall\tau$$

where

$$\delta_{bc\tau}=\begin{cases}1 \text{ if crop } c \text{ is grown on plot } b \text{ at time } \tau\\ 0 \text{ otherwise}\end{cases}$$

$y_{cb\tau}$ denotes the yield at time τ for crop c on plot b that depends on rainfall $\widetilde{R_\tau}$, irrigation $W_{bc\tau}$ and production costs $X_{cb\tau}$ (inputs). Variables $\theta_{\widetilde{P_{c,\tau}}}$, $\theta_{y_{cb\tau}}$, $\theta_{X_{bc\tau}}$ are penalty factors on crop prices, yield and production costs, respectively, due to social, economic, and environmental constraints. These factors are used to introduce additional farm-specific fixed costs on inputs and/or farm- and crop-specific crop yield factors and/or shifts in crop price; their purpose is to incorporate a more realistic representation of cost and crop yield beyond the representative farmer paradigm. These penalty factors are discussed in more detail in section 2 entitled "Formalism 2: IF-THEN-ELSE decision rules for crop selection and adaptation"), on tactical decisions.

Crop yield $y_{cb\tau}$ results from agricultural management rules that are operational decisions made at a daily scale and detailed in section 3 entitled "Formalism 3: Graph of activities for crop management decisions"). The strategic model interacts with the operational model. It provides specific cropping conditions for a crop as input data to the operational model and receives the output data on yield.

Let $\pi_t^*(I_t, W_t, R_t, P_t)$ be the maximum profit for a given investment in irrigation I_t for year t,

$\pi_t^*(I_t, W_t, R_t, P_t) = \max_{\delta_{bc\tau}}\left[\sum_{\tau=k_1}^{S_2}\sum_{b=1}^{B}\sum_{c=1}^{C}\delta_{bc\tau}\pi_{cb\tau} \,\middle|\, I_t, W_t\right].$

The stochastic dynamic programming problem can be solved using a variety of methods. Since no condition is imposed a priori on the terminal level of water availability or irrigation capital stock, we assume that it is an infinite horizon problem. A typical way to solve an infinite-horizon problem is the collocation method applied to the Bellman equation for dynamic programming. The problem above can be written equivalently in terms of the value function V(W_t):

$\mathrm{V}(W_t) = \max_{I_t}\{\pi^*(I_t, W_t, R_t, P_t) - r_{It}I_t + (1+r)^{-1}E_{\tilde{R}}E_{\widetilde{GW}}E_{\tilde{P}}\mathrm{V}(W_{t+1})\}\ \ \forall t,$

where

$W_{t+1} = E_{\tilde{R}}E_{\widetilde{GW}} f(W_t, I_t, \widetilde{R_{\tau+1}}, \widetilde{GW_{\tau+1}}).$

The value function, taking the state variable as a single argument, is conveniently approximated by a widely-used method based on Chebychev polynomials (see Bertsekas, 2011). The optimization problem is solved simultaneously in the optimal values of control variables and the Chebychev coefficients of the parametric approximation of the value function.

Each year farmers make decisions about irrigation investment and crop allocation to achieve the highest long-term profit, given the impact of current investment on future income streams (through modified water availability from investment in irrigation).

Based on the 27 interviewed farmers and expert assessments, crop choices were clearly dependent on irrigation water access. The survey of 680 farms showed that some farmers had till 12 borewells on their farm. We deduced that increase the farm irrigation capacity is an implicit decision in farmers' strategy. To structure our model, we identified four steps in the farmers' investment decision plan:

Step 1: Farmers form expectations for future crop prices, rainfall and water table level in their borewell.

Step 2: They decide whether to invest in upgrading their irrigation equipment.

Step 3: Given the possibly upgraded equipment, farmers decide which crops to grow on their plots for each sub-season τ that will not only maximize their profit in the long term but also consider the social, economic, and environmental constraints that may influence crop price, production costs and yield (penalty factors) (see section 2 entitled "Formalism 2: IF-THEN-ELSE decision rules for crop selection and adaptation"), on tactical decisions).

Step 4: On each plot and for each sub-season τ, given the irrigation equipment and the selected crop, farmers apply a set of agricultural management rules (see section 3 entitled "Formalism 3: Graph of activities for crop management decisions"), on operational decisions) to obtain the "best" crop yield, conditional on actual climatic and groundwater table conditions.

2) Formalism 2: IF-THEN-ELSE decision rules for crop selection and adaptation

A formal way to describe decision-making in the medium- or short-term in a simulation model is to state decision behavior through a set of decision rules. Decision rules use a specific descriptive language whose syntax is based on formal IF-THEN-ELSE rules, which have three main sections (Donatelli et al. 2006): i) an input or indicator, which refers to the state of the system (e.g. physiological state, air temperature, leaf area index); ii) a parameter or threshold (e.g., minimum temperature, soil moisture threshold to trigger irrigation); and, iii) a true/false output leading to an action (e.g., start irrigation, start sowing). It is written as a Boolean condition: "IF<*indicator*><*operator*><*threshold*> THEN <*action1*> ELSE <*action2*>". A decision rule forms the elementary block of a decision model, and the aggregation of elementary rules builds the structure of the decision rule-based model.

Decision rules describe decision-making processes by dynamically relating the state of the simulated system (input or indicator) to decisions that trigger actions (true/false output) based on predefined conditions and threshold values (Bergez et al. 2006). The actions performed are considered to originate from a reactive behavior of the decision-maker since they depend on climatic conditions, the state of the system, and the calendar date.

The analysis of the 680 surveys and associated typology showed that crop choice depends on social characteristics such as the caste, the panchayat, the structure of the household, and the farmer education. The 27 interviewed farmers also highlighted economic and agronomic necessary conditions for their crop choice decisions such farm size, market prices, contract opportunities offered by marigold companies, grain stocks, farm location from a local market, a main road, or a forest, rainfall expectations or monsoon expectation, borewell yield and farm equipment.

We give three examples of decision rules to better explain this concept:

- In kharif, when farmers have plot b near road b_{road}, they will likely grow beetroot, with the expectation of obtaining harvest contracts when the crop ripens. Otherwise, they will grow a vegetable that is expected to bring a higher profit (i.e., tomato, bean, potato), which is an easy option for obtaining cash rapidly by being sold at local markets. We translated this into the following decision rules:

IF $b_{K_1} = b_{road}$ {

$c_{b_{K_1}} =$ beetroot}

$ELSE$ {

IF $\pi_{tomato\ b\tau} > \pi_{bean\ b\tau}$ & $\pi_{tomato\ b\tau} > \pi_{potato\ b\tau}$ {

$c_{b_{K_1}} =$ tomato}

$ELSE$ {

IF $\pi_{bean\ b\tau} > \pi_{tomato\ b\tau}$ & $\pi_{bean\ b\tau} > \pi_{potato\ b\tau}$ {

$c_{b_{K_1}} =$ bean}

$ELSE$ {

$c_{b_{K_1}} =$ potato}

}

}

- If farmers use drip irrigation, they prefer to grow banana rather than turmeric because it is easier and cheaper to maintain drip irrigation in the same plot for three years (the banana growth period) than to remove and replace the irrigation lines after 11 months (the turmeric growing period). We translated this into:

IF $EQUIP_{irrigation} =$ drip {

$c_{b_\tau} =$ banana}

$ELSE$ {

$c_{b_\tau} =$ turmeric}

- Farms located a distance *d* less than one kilometer from the forest experience wild animal damage that dramatically reduces their yields of cereals and millets (sorghum and finger millet). Thus, on rainfed plots, farmers prefer to grow fiber crops (cotton) or flowers under contracts (marigold). We translated this into:

IF $d \leq 1$ & $\pi_{marigold\ b\tau} > \pi_{cotton\ b\tau}${

$c_{b_{K_1}} =$ marigold}

$ELSE$ {

IF $d \leq 1$ & $\pi_{cotton\ b\tau} > \pi_{marigold\ b\tau}${

$c_{b_{K_1}} =$ cotton}

$ELSE$ {

$c_{b_{K_1}} =$ sorghum}

}

Decision rules express the conditions under which farmers favor one crop over another. These conditions influence crop price, production costs and yield to the point that they economically force farmers to favor a specific crop. In the first example, proximity to the road increases the chances that passing merchants will offer harvest contracts when beetroots ripen. These contracts ensure that farmers have a fixed price and free them from harvesting; so, no labor or time costs occur at harvest. Fixing the price minimizes risks of variability at selling, reduces labor and time at harvest, and decreases production costs. In the second example, selecting three-year crops, such as banana, allows farmers to maintain the drip equipment during the entire production time, while with yearly crops, irrigation lines must be removed and replaced each year. Thus, maintaining lines for a longer time reduces investment in new lines, is less time consuming, and reduces production costs. Wildlife damage to cereals and millet decreases crop yield, which directly determines profit.

We integrated these tactical decision rules into the strategic model via penalty factors on crop prices, yield and production costs ($\theta_{\widetilde{P_{c,\tau}}}$, $\theta_{y_{cb\tau}}$, $\theta_{X_{bc\tau}}$, respectively). It ensures that the strategic model selects a cropping system though an economic approach constrained by social, agronomic and economic characteristics other than just prices and costs like it is common in profit optimization approaches (see section 1 entitled "Formalism 1: Stochastic dynamic programming formalism for the investment decision"). Thus, it incorporates a more realistic representation of cost and crop yield beyond the representative farmer paradigm.

Crop selection is planned in two steps:

Step 1: At the beginning of each season (kharif or rabi or summer), farmers update their expectations for future crop prices, rainfall and water table level in the borewell based on the new information they obtained from the biophysical and external systems.

Step 2: Depending on whether their expectations for borewell yield, rainfall, and prices for the season have changed since the beginning of the year (1^{st} of January), they review their cropping system. Farmers apply the decision framework used to determine the strategic decisions. They select the cropping system that maximizes their profit while following decision rules that were formerly expressed through penalty factors during the optimization process.

3) Formalism 3: Graph of activities for crop management decisions

Operational decisions lead to the technical production activities that the farmer performs at the plot level. Based on prior experiences, goals and the expected likelihood of significant events, the farmer reflects on a work plan that coordinates the combination of activities to be performed and manages resources at the farm scale. Hence, we considered work activity the basic unit of analysis. To identify crop management activities, we used data from multiple surveys and studies. First, the 52 monitored experimental plots provided observed quantitative data about crop production and crop management. Then the interviews of 27 farmers helped in identifying decision rules for crop operations. We also surveyed seed retailers and Panchayats (village leaders) to learn about recommended crop management

The design of the conceptual operational decision model is greatly supported by the decision formalism in the RECORD platform (Bergez et al. 2013). In RECORD's decision formalism, the agent system is composed of a knowledge base and a graph of activities. The knowledge base collects information that the farmer obtains from the biophysical sub-system when monitoring and observing the environment. The graph of activities represents the farmer's work plan and relies on the knowledge base to activate or disable technical operations. An activity denotes a task, which is something to be done to a biophysical object or location (e.g. sowing operation). Rules control the start of the activity by ensuring conditions necessary to perform the operation. A deeper description of this formalism is found in Bergez et al. (2016).

Integrated into the graph of activities is the well-known sequence of crop management: land preparation, sowing, irrigation, fertilization, pest treatment, weeding and harvest. Take the example of a simplified crop management composed of two steps: sowing and harvesting. Under rainfed conditions in the Berambadi watershed, sunflower should be sown between April 8 and June 20. Three rules may determine the shift in state from "wait" to "start". The first tests for optimal conditions, the second relaxes the conditions, and the third forces the activity to start. Ideally, the farmer will start sowing when soil characteristics (moisture and temperature in the upper 15 cm) are favorable for seed germination and if at least 40 mm of rain fell in the past 10 days. If sowing has not occurred by June 1, the farmer relaxes the threshold condition for rainfall to 10 mm. In the worst case, if sowing has not occurred by June 19, the farmer will sow on June 20 regardless of the soil and weather conditions. The sowing activity is written as follows:

Activity = sowing

State = wait

Precedence effect = start when previous harvest is finished

Earliest beginning date =April 8

Latest beginning date = June 20

Optimal rule:

> Soil moisture: soil water reserve/soil capacity>= 0.6
>
> Soil temperature: temperature>= 6 $\mathring{C}$
>
> Rainfall: $\sum_1^{10} rainfall(day - j) \geq 40\ mm$

Relaxed rule:

> Relaxed date = June 1
>
> Rainfall: $\sum_1^{10} PP(day - j) \geq 10\ mm$

Forced rule:

> Forced date: June 20

Output Function:

> Sowing density: density = 16 seeds/m^2
>
> Sowing depth: depth = 6 cm

Harvest makes sense only if sowing has occurred (precedence effect). It can start from August 8 to October 15; the crop stage should last 80-110 days after sowing, and no rain can have fallen in the past two days. In bad conditions, the farmer will always harvest after 110 days after sowing. The harvest activity is written as follows:

Activity = harvest

State = wait

Precedence effect = start when sowing is finished

Earliest beginning date =August 8

Latest beginning date = October 15

Optimal rule:

> Minimum crop stage = sowing date + 80 days
>
> Maximum crop stage = sowing date + 110 days
>
> Rainfall: $\sum_1^{2} rainfall(day - j) < 1\ mm$

Forced rule:

> Forced crop stage: sowing date + 110 days

Besides having flexibility in timing, Indian farmers adapt their plans when the risk of crop failure is too high. Farmers check the sowing conditions and, instead of forcing sowing, change the crop. After sowing, farmers monitor germination and check whether it is worth letting the crop grow. They may reseed the crop, remove it and change the crop, or leave it as-is. This reactive behavior can be modeled into the graph of activities. When sowing cannot be performed within the time window, the activity is detected to have failed. Then, the output functions cancel the subsequent planned activities and load a new plan for the new crop. At germination, the farmer considers field observation as an activity to perform after sowing. The Boolean condition tests whether the germination rate exceeds 60%. If false, the output function will likewise cancel subsequent activities and load a new plan to manage the new crop. The germination activity check is written:

Activity = check germination

State = wait

Precedence effect = start when sowing is finished

Earliest beginning date =April 18

Latest beginning date = June 30

Optimal rule:

Minimum crop stage = sowing date + 10 days

Maximum crop stage = sowing date + 10 days

Germination: germination rate $\geq$ 60%

Output function:

Fail plan: for all activities with state=wait, do state=failed

Load new plan: load new graph of activities

We summarized the crop management plan of the three activities described above (sowing – germination check – harvest) as a decision tree to help see all possible situations that depend on the conditions (Figure 5.4). Notice that when germination fails, the subsequent activity of the plan (harvest) also fails; in this case, a new graph of activities (crop management plan) is loaded.

To ensure consistency with the dynamic process of investment decisions (see section 1 entitled "Formalism 1: Stochastic dynamic programming formalism for the investment decision") ,yields within the profit function come from the graph of activities process used to decide about crop operations.

The farmer's crop management decision plan is as follows:

Step 1: Once farmers choose the crop to grow on each plot at the beginning of the season (kharif or rabi or summer), they check external and biophysical conditions daily to decide whether conditions are favorable to start land preparation.

Step 2: When conditions are favorable, they check whether resources (labor and equipment) are available to perform the operation.

Step 3: When conditions are favorable and resources are available, farmers plow the plot; otherwise, the operation's priority for the resource increases so that the next time conditions are favorable, it has first priority.

Step 4: Once an operation is performed or the time window in which the operation should have occurred is over, the next operation (sowing) may start. Once again, farmers check conditions and resources to decide when to initiate it.

Farmers repeat these steps until the end of the plan (i.e., harvest).

Integrating formalisms within the three dimensions of the decision-making process

In NAMASTE, the three stages of the decision-making process are described as three decision models (Figure 5.5).

1) The strategic model simulates the strategic decision stage of the farmer. The model integrates the three formalisms so that at the beginning of the year (1st of January), the strategic decision phase for investment in irrigation equipment uses the crop selection and decisions about cropping operations to estimate yield, production costs, income, and profit.
2) The tactical model simulates the tactical decision stage of the farmer. The model integrates the three formalisms so that at the beginning of the season (kharif, rabi or summer), the profit optimization formalism is re-run with the irrigation investment chosen and uses the crop selection and decisions about cropping operations to estimate yield, production costs, income, and profit using updated information about the environment.
3) The operational model simulates the operational decision stage of the farmer. The model uses the formalism for cropping operations each simulated day to decide about crop management.

5.3.3. Description of the other systems in the model

The biophysical system

1) The crop model

The crop and soil system is represented by the STICS model. STICS is a dynamic model that simulates, at a daily time-step, the operating of a crop-soil system over one or several crop cycles (Brisson et al. 1998). It was selected for its adaptability to many crop types, its robustness in a wide range of soil and climate conditions and its modularity (Brisson et al. 2003). It has been successfully used in spatially explicit applications and coupled with hydrological models at the watershed scale (Beaujouan et al. 2001).

During a simulation, STICS considers the crop, crop-management practices and environmental limits, such as water and nitrogen stress. It predicts crop growth and harvest and environmental dynamics, such as water drainage and nitrogen leaching.

Using the Generalized Likelihood Uncertainty Estimation approach, crop parameters for leaf area index, biomass and yield production were estimated for the main crops of the Berambadi watershed so that the calibrated STICS simulated crops and root-zone soil moisture relatively accurately (Sreelash et al. 2013). STICS receives the crop operations and parameters applied to the plot from the operational decision model. It returns information about crop stage, yield, soil characteristics and water uses and drainage.

2) The hydrological system

The hydrological system is represented by two coupled models:

- AMBHAS (Tomer 2012) is a distributed groundwater model that simulates dynamics of daily groundwater level. The model is based on equations from McDonald & Harbaugh (1988). It predicts daily groundwater level, actual net recharge and discharge. Net recharge is predicted from the amounts of water drained below the soil profile and required for crop irrigation predicted by STICS.
- The PUMP model couples STICS and AMBHAS to predict the water available for irrigation, based on the groundwater level predicted by AMBHAS and the electricity available from the ELECTRICITY model. First, it calculates water table depth below the soil surface as:

WaterTableDepth = max (0.0, Altitude – H (-1))

It estimates pump flow as:

PumpFlow = 0 if WaterTableDepth > WellDepth

PumpFlow = max(0, 79.9308 × $\mathrm{WaterTableDepth}^{-0.728}$)

Finally, it predicts the water available for irrigation based on the pump flow and pumping duration:

AvailableWater = max(0.0, PumpFlow() × PumpingDuration()

The operating sub-system

The operating sub-system transforms the farmer's decisions into executable actions on the biophysical sub-system. Executing the decision is a physical process that disrupts the biophysical system. The operating system is the physical part of the agent, while the decision system is the cognitive part of the agent. It represents the physical act of going to the plot and executing an action (Cros et al. 2003; Martin-Clouaire and Rellier 2003; Cerf et al. 2009).

Each time the decision sub-system is activated, the decided activity and its requirements are handed over to the operating sub-system by posting an event to be performed in its agenda. The operating sub-system looks for specific variables from the biophysical and external systems that are used by the execution conditions (predicates) of an activity and checks that requirements are met to execute the operation. The operating sub-system observes the external variables and calculates the data used by the predicates to verify whether the conditions allow the activity to be executed.

The operating sub-system also manages allocation of the farm's physical resources. It operates as a mediator that dynamically manages conflicts between activities by using rules to allocate resources and determine the order in which activities will be executed. Prioritization is supervised by rules that define a temporal ranking among activities that may be executed simultaneously (e.g. sowing has priority to harvest, irrigation has priority to weeding) . Ranks can be reviewed by other rules that update the priority.

The operating sub-system informs the decision system that an activity has been executed or failed to be executed so that the decision system can proceed with the plan or adapt it. It also serves as the interface that monitors the plot and observes the biophysical and external systems. Observations concern the effects of activities on the biophysical sub-system and on the pool of resources, and also on the natural changing states of the systems.

The external system

1) The climate

Daily and expected rainfalls are simulated by the WEATHER model. Climatic series are obtained from a local meteorological station and water gauges. Concerning future climate, farmers form subjective distribution that takes the form of a discrete distribution based on past events.

2) The market

Current and expected crop market prices are simulated by the MARKET model. Price series are obtained from the Indian Department of Agricultural Marketing and Karnataka State Agricultural Marketing Board. For each market, the model provides the commodity, the variety, the grade, and the volume of arrivals on the market and the minimum, maximum and median prices for the day. Expectations formed by farmers on future crop prices are myopic and based on past realizations of market prices.

3) The village

Each village has a labor pool and an equipment pool for crop production. All farmers in the village use labor and equipment from the village. Certain activities, such as weeding and harvesting, require so much labor that two or three farmers can use all of the day's available labor. Farming activities depend on neighboring farmers' practices. We observed a rotation of labor and equipment among farms in the village. The VILLAGE model manages the labor and equipment among all village farmers. It acts as a resource manager and attributes resources to the first enquirer. This resource planning is performed at the village scale and interacts with the operating decision model of each farmer in the village.

4) The power supply

The ELECTRICITY model predicts the number of hours of electricity available daily. The model is particularly useful when testing scenarios of the temporal distribution and fees of electricity.

5.4. DISCUSSION

The agricultural research community has a particular interest in modeling farming systems. We identified three main ideas in the scientific literature that are interesting to consider when modeling a farming system: i) a systemic representation is relevant (Martin et al. 2011b; Tanure et al. 2013), ii) dynamic processes bring the farming system to life (Bellman 1954; Mjelde 1986; Cerf and Sebillotte 1988; Papy et al. 1988; Osman 2010), and iii) farmers' decision-making processes are flexible and adaptive over time and space (Grothmann and Patt 2003; Smit and Wandel 2006; Darnhofer 2014). We developed an original representation of farming systems that integrates these aspects into a new conceptual model. Although it was built to address critical issues of groundwater management and farming practices in the semi-arid region of the Berambadi watershed, its structures and formalisms are well-suited to other farming systems. Indeed, the systemic representation of the farming system can be applied to any farming system that considers the farm as being composed of decisional and biophysical components that interact with an external system that simulates the pressure and conditions of the farming environment. The biophysical system is usually simplified to a crop growth model but can also include a groundwater or river model for irrigation systems. Climate and crop market prices are the basic components of the external system.

An increasing amount of research considers farm management as a flexible and dynamic process. Basically, farmers adapt their practices to the biophysical sub-system and the external system. Our model allows the adaption of decisions in time (delay an operation) and considers crop failure for some operations (e.g., sowing, germination). Our approach would be particularly useful for models in semi-arid and arid areas with limited irrigation water access and high evaporative stress. The most interesting part of our model for future work is the decision sub-model itself. We used the basic definition of Le Gal et al. (2011), which divides a decision into a set of interconnected decisions made over time and at multiple spatial scales.

Sequential representation is particularly interesting and appropriate to model the entire decision-making processes from strategic to tactical and operational decision (Risbey et al. 1999; Le Gal et al. 2011). Decisions made at one of these levels may disrupt the initial organization of resource availability and competition among activities over the short term (e.g., labor availability, machinery organization, irrigation distribution) but also lead to reconsideration of long-term decisions when the cropping system requires adaptation (e.g., change in crops within the rotation, consequences on the effect of the previous crop). In the current agricultural literature, these consequences on long- and short-term organization are rarely considered, even though they appear an important driver of farmers' decision-making (Daydé et al. 2014).

In the long term, uncertain events are difficult to anticipate due to the lack of knowledge about the environment. A common way to address uncertainty in long-term decisions is to consider that farmers have reactive behavior due to insufficient information about the environment to predict a shock and should be modeled with a dynamic model (Heidhues 1966; Barbier and Bergeron 1999; Wallace and Moss 2002; Domptail and Nuppenau 2010). In the medium and short terms, the temporal scale is short enough that farmers' expectations of shocks are much more realistic. Farmers observed new information about the environment, which provided more self-confidence in the event of a shock and helped them to anticipate changes. Anticipation is considered as a static process that is often modeled with a static model (Cros et al. 1999; Ripoche et al. 2011; Martin et al. 2011b; Chardon et al. 2012).

We proposed in this paper to combine several formalisms within an integrated model in which strategic and tactical adaptations and decisions influence each other to model adaptive behavior within farmers' decision-making processes. To model three stages of decision, we combined economic, decision-rule, and activity-based models. This structure can be used to model normal decision situations, such as selecting a cropping system for the long term, the variety and management associated with it in the medium term, and then daily crop-management practices.

This integrated structure combine models of both complete rationality (clearly expressed goals from the beginning and knows all the relevant alternatives and their consequences (Couture and Martin-Clouaire 2013)) and bounded rationalities (limited by the information available, cognitive limitations of the mind and the finite timing of the decision (Simon 1950; Cyert and March 1963)). The economic model describes long-term decisions of farmers whose concerns are mainly with the strategic positioning and sustainability of the farms while the decision-rule, and activity-based models describe medium and short term decisions of farmers whose concern are mainly with implementation than sustainability addressing issues at increasingly greater details and more localized levels.

A fundamental principle when building a model is to produce a simplified representation of the reality. First, the case based study done over 27 farmers revealed that the caste, the panchayat, the structure of the household, the farm size and the farmer education contribute to the farmer behavior. However, the economically rational decision described in the strategic model of NAMASTE is not at first glance the best appropriate in accounting for diverse rationalities that different types of farmers employ in real life while making decision on farm management (Karali et al. 2011; Feola et al. 2015).This choice was necessary to consider our approach of farm modeling within the AICHA project. The micro-economic assumptions on individual rationality, homogeneity and single minded utility maximization offer analytical tractability and readily extrapolation to the watershed scale. Our model is mainly based on economics and natural science and partially uses social sciences other than economics. We refer to social embeddedness of farmer behavior through the use of a typology and penalty factors on crop prices, yield and production costs that reflect the social, economic, and environmental constraints that motivate farmers' decisions as embedded in specific agricultural systems. Second, even if the majority of farmers surveyed answered that maximizing profit was their main objective while farming, the literature and expert assert that in South India, farmers also seek to secure a balanced food supply for the household which justify why an important part of them are also growing subsistence crops.

This conceptual model was essential to move toward a computer model useful for future simulations. The model is under implementation in the RECORD platform. Frameworks and formalisms developed in our conceptual model are appropriate and implementable in this platform. It provides tools for analyzing, evaluating, and optimizing agronomic, environmental and economic criteria. A baseline scenario will be developed to simulate current farming practices in the Berambadi watershed and predict their influences on the groundwater level. Then scenarios with changes in climate, groundwater table, and government subsidies will be developed to predict their impacts on cropping systems and the water table. Modeling agricultural production scenarios can effectively help stakeholders make decisions about regulations and resource restrictions and encourage new practices to be recommended to farmers.

5.5. CONCLUSION

We developed an original conceptual model of a farming system that combines relevant principles highlighted in the scientific literature. The model was initially developed to address critical issues of groundwater depletion and farming practices in a watershed in southwestern India. Its structure, frameworks and formalisms can be used in other agricultural contexts. Our application focused on water management in semi-arid agricultural systems, but it can also be applied to other farming systems to confirm the re-usability and applicability of the framework.

ACKNOWLEDGEMENTS

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TABLE CAPTION

Table 5.1: Definitions of symbols in section 0

Symbol	Definition
t	Year
τ	Season
I_t	Investment in irrigation equipment
r_{It}	Unit cost of investment in irrigation
$\bar{W}_t$	Water available for irrigation
b	Bele
c	Crop
$C_{W\tau}$	Unit cost of water
$\widetilde{R_{a\tau}}$	Climate event (rainfall)
$\widetilde{GW_{a\tau}}$	Groundwater level
$\widetilde{P_{c,t}}$	Crop prices
$PW_{b\tau}$	Proportion of water available to each plot
r	Discount rate
$\pi_{bc\tau}$	Profit
$y_{cb\tau}$	Crop yield
$X_{cb\tau}$	Production costs
$\theta_{\widetilde{P_{c,\tau}}}$	Penalty factors on crop prices
$\theta_{y_{cb\tau}}$	Penalty factors on yield
$\theta_{X_{bc\tau}}$	Penalty factors on production costs

FIGURE CAPTION

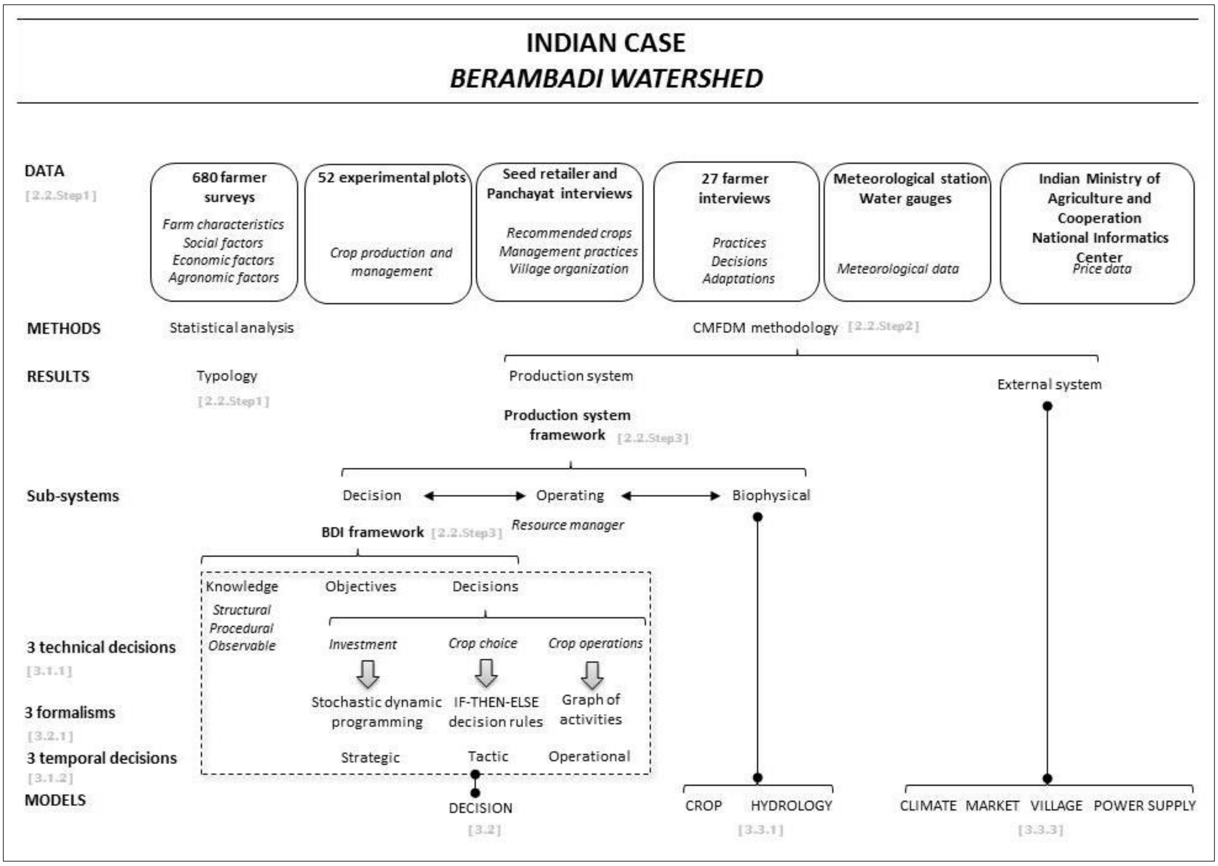
Figure 5.1: Overview of the conceptual model from data collection to coupled models. Data and statistical analysis used on the 680 farmer surveys as well as the farm typology are described in section 2.2. Step1. The CMFDM method (standing for Conceptual Modeling of the Farmer agent underlying Decision-Making processes) is described in section 2.2.Step2. Two main systems are identified: the production system and the external system. Focus is made on the production system. The Production system framework and the Belief-Desire-Intention (BDI) framework are described in section 2.2.Step3. The decision sub-model is characterized by three technical decisions (investment, crop choice, crop operations) (section 3.1.1). The formalisms used to represent these decisions are described in section 3.2.1. The three temporal dimensions of the decision process (strategic, tactic, operational) are described in section 3.1.2. The final model is composed of a decision sub-model (section 3.2.), a biophysical sub-model (section 3.3.1) and an external system (section 3.3.3).

Figure 5.2: Groundwater level (GWL) in the Berambadi watershed. A) Stream drainage and depth to groundwater level, B) topographic elevation and water table level.

Figure 5.3: The farming system as a Decision-Operating-Biophysical System framework. Presentation of the sub-models used in the conceptual model. The Beliefs, Desires, and Intentions framework provides structure to the decision sub-system. It breaks the system down the system into these three entities, each composed of several items. Beliefs are composed of structural, procedural, and observable knowledge, as well as strategic, tactical and operational intentions (adapted from Rao & Georgeff, 1991).Dynamic flow of information exchanged during the decision-making process from strategic to tactical and operational decisions.

Figure 5.4: Decision tree describing a simplified crop management plan: sowing, germination check, and harvest. Rules, predicates and output functions are summarized in the text.

Figure 5.5: Three integrated stages of decisions in time, with broad knowledge at the beginning of the year that becomes more precise as time passes from seasons to days. The strategic decision about investing in irrigation equipment uses formalisms for crop selection and cropping operations. Decisions about crop selection are re-used at the tactical decision stage based on updated knowledge and expectations for the environment over the coming season. Decisions about cropping operations are re-used at the operational decision stage based on daily observations of the environment.



INDIAN CASE
BERAMBADI WATERSHED
DATA
[2.2.Step1]
680 farmer surveys
Farm characteristics
Social factors
Economic factors
Agronomic factors
52 experimental plots
Crop production and management
Seed retailer and Panchayat interviews
Recommended crops
Management practices
Village organization
27 farmer interviews
Practices
Decisions
Adaptations
Meteorological station
Water gauges
Meteorological data
Indian Ministry of Agriculture and Cooperation
National Informatics Center
Price data
METHODS
Statistical analysis
CMFDM methodology [2.2.Step2]
RESULTS
Typology
[2.2.Step1]
Production system
External system
Production system framework [2.2.Step3]
Sub-systems
Decision
Operating
Biophysical
Resource manager
BDI framework [2.2.Step3]
Knowledge
Structural
Procedural
Observable
Objectives
Decisions
Investment
Crop choice
Crop operations
3 technical decisions
[3.1.1]
Stochastic dynamic programming
IF-THEN-ELSE decision rules
Graph of activities
3 formalisms
[3.2.1]
3 temporal decisions
[3.1.2]
Strategic
Tactic
Operational
MODELS
DECISION
[3.2]
CROP
HYDROLOGY
[3.3.1]
CLIMATE
MARKET
VILLAGE
POWER SUPPLY
[3.3.3]

Figure 5.1

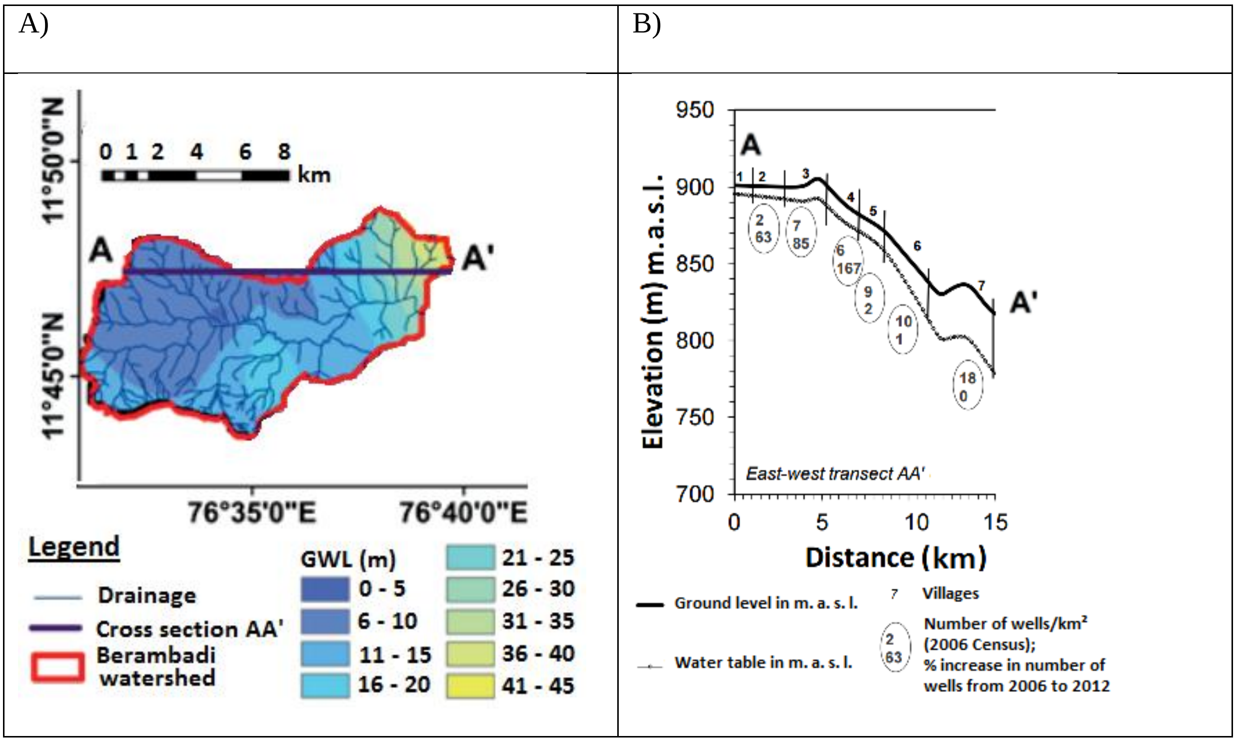

A)
B)
0 1 2 4 6 8 km
A
A'
11°50'0"N
11°45'0"N
76°35'0"E
76°40'0"E
Legend
Drainage
Cross section AA'
Berambadi watershed
GWL (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
26 - 30
31 - 35
36 - 40
41 - 45
Elevation (m) m.a.s.l.
950
900
850
800
750
700
East-west transect AA'
0
5
10
15
Distance (km)
Ground level in m. a. s. l.
Water table in m. a. s. l.
Villages
Number of wells/km² (2006 Census);
% increase in number of wells from 2006 to 2012

Figure 5.2

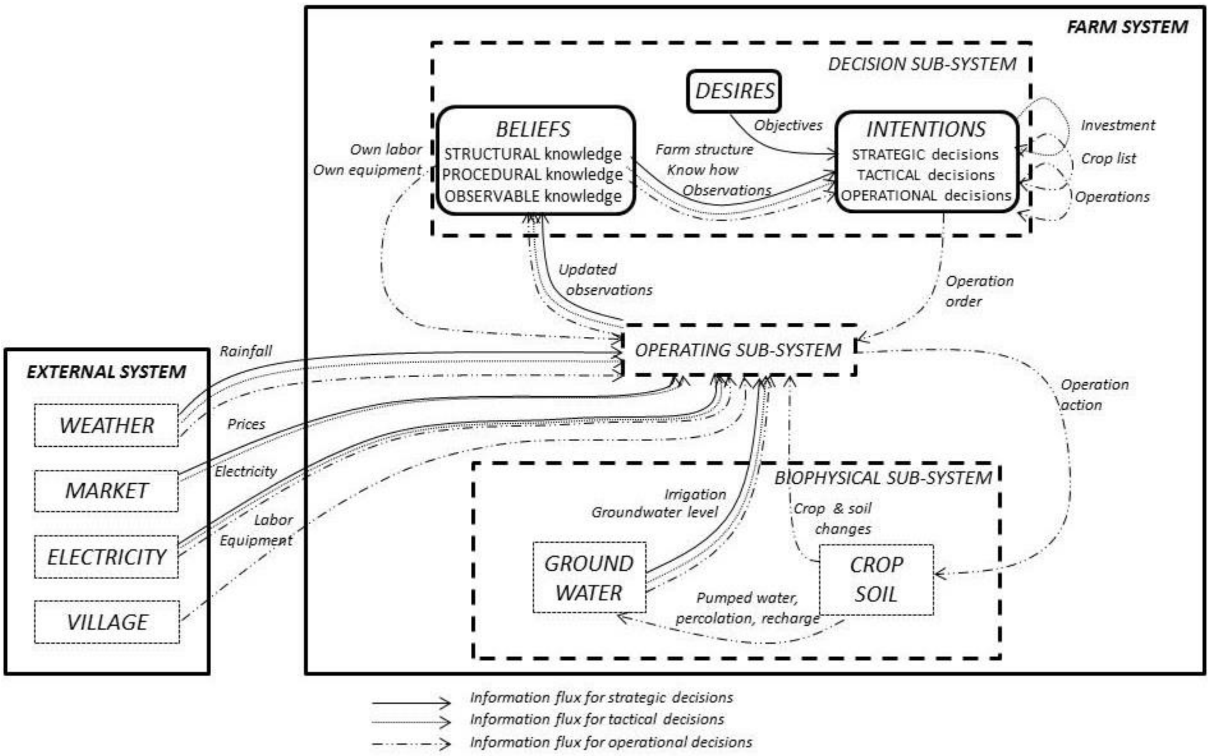
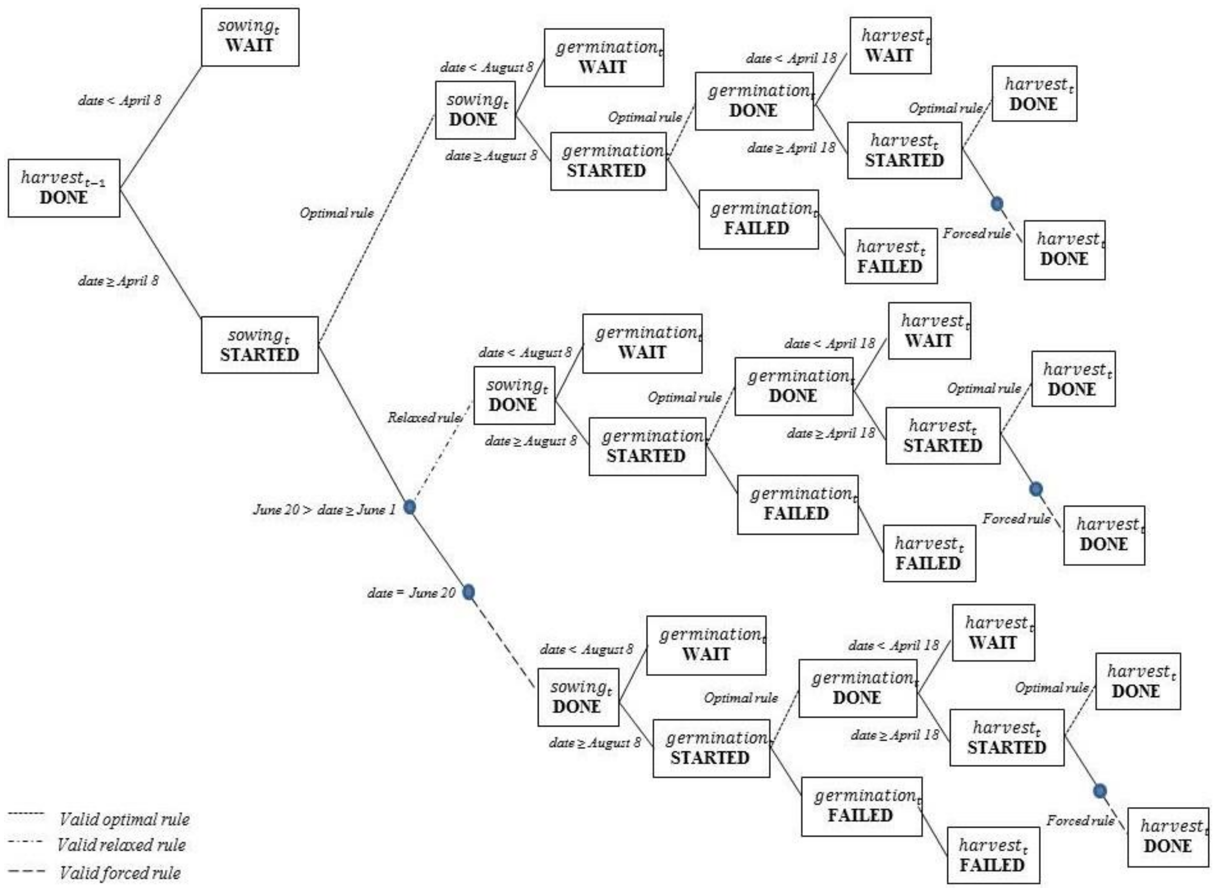

FARM SYSTEM
DECISION SUB-SYSTEM
DESIRES
Objectives
BELIEFS
STRUCTURAL knowledge
PROCEDURAL knowledge
OBSERVABLE knowledge
Farm structure
Know how
Observations
INTENTIONS
STRATEGIC decisions
TACTICAL decisions
OPERATIONAL decisions
Investment
Crop list
Operations
Own labor
Own equipment
Updated observations
Operation order
OPERATING SUB-SYSTEM
Operation action
EXTERNAL SYSTEM
WEATHER
MARKET
ELECTRICITY
VILLAGE
Rainfall
Prices
Electricity
Labor
Equipment
BIOPHYSICAL SUB-SYSTEM
Irrigation
Groundwater level
Crop & soil changes
GROUND WATER
CROP SOIL
Pumped water, percolation, recharge
Information flux for strategic decisions
Information flux for tactical decisions
Information flux for operational decisions

Figure 5.3



harvest t−1 DONE
date < April 8
sowing t WAIT
date ≥ April 8
sowing t STARTED
Optimal rule
date < August 8
sowing t DONE
germination t WAIT
date ≥ August 8
germination t STARTED
Optimal rule
germination t DONE
germination t FAILED
date < April 18
harvest t WAIT
date ≥ April 18
harvest t STARTED
Optimal rule
harvest t DONE
Forced rule
harvest t FAILED
Relaxed rule
June 20 > date ≥ June 1
date = June 20
Valid optimal rule
Valid relaxed rule
Valid forced rule

Figure 5.4

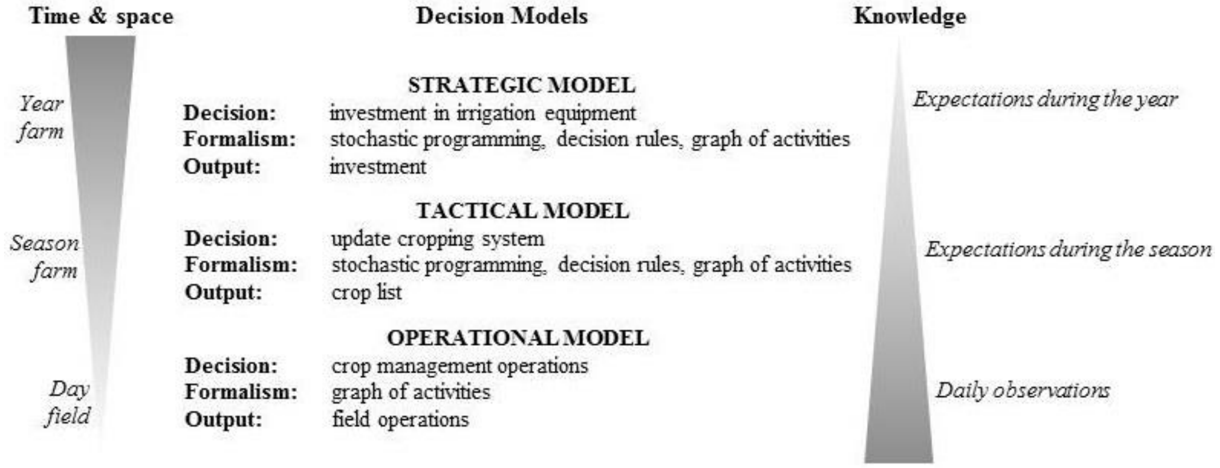

Time & space
Decision Models
Knowledge
Year
farm
STRATEGIC MODEL
Decision: investment in irrigation equipment
Formalism: stochastic programming, decision rules, graph of activities
Output: investment
Expectations during the year
Season
farm
TACTICAL MODEL
Decision: update cropping system
Formalism: stochastic programming, decision rules, graph of activities
Output: crop list
Expectations during the season
Day
field
OPERATIONAL MODEL
Decision: crop management operations
Formalism: graph of activities
Output: field operations
Daily observations

Figure 5.5

Chapter 6

A stochastic dynamic programming approach to analyze adaptation to climate change - application to groundwater irrigation in India

Marion Robert*[1], Jacques-Eric Bergez[1] and Alban Thomas[2]

[1] AGIR, Université Fédérale de Toulouse, INRA, INPT, F-31326 Castanet-Tolosan, France
[2]Toulouse School of Economics, INRA, University of Toulouse, F-31000 Toulouse, France
* Corresponding author: (marion.robert@inra.fr)

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Agricultural sustainability under climate change is a major challenge in semi-arid countries, mainly due to rare or depleted water resources. This article explores short- and long-term consequences of farmers' adaptation decisions about groundwater resources under several climate change scenarios. We modeled farmer decisions about crop choice, investment in irrigation and water application rates using a stochastic dynamic programming model with discrete time and control variables. We also investigated the performance of water management policies for groundwater resource depletion, and considered adaptive farmer decisions about irrigation and crop systems. Several sources of risk were considered: rainfall average and variability, crop market prices, crop yield and borewell failure. Policy simulations were performed with a calibrated version of the stochastic dynamic model, using data from a field survey in the Berambadi watershed, Karnataka state, southern India. The most relevant and novel aspects of our model are i) the consideration of investment decisions about irrigation over a long-term horizon, ii) the consideration of several water management policies, iii) the detailed description of farmers' water practices and representation of crop choice based on the agricultural season.

Keywords: (D) OR in agriculture; (I) Stochastic programming; (D) OR in environment and climate change; (D) Strategic planning; (B) Scenarios.

6.1. INTRODUCTION

Climate change is a significant challenge for sustainable agricultural production in the coming decades, especially since global food demand is expected to double by the year 2050. Predictions of climate change impacts indicate a reduction in most crop yields under both irrigated and rainfed conditions, an increase in weeds, diseases and pests and changes in crop development and pollination periods (Kahil et al. 2015).

Agricultural systems in semi-arid areas depend greatly on irrigation and encounter increasing challenges due to climate change (e.g. growing uncertainty about the performance of strategies for adapting to climate change, severe depletion of natural resources), high volatility in crop market prices, rises in energy costs and greater pressure from public regulations (e.g. agricultural, environmental and health policies). In the Deccan Plateau in India, aided by state policy that subsidizes electricity and improved irrigation technology (e.g. new drilling and submersible pump techniques), the countryside has witnessed the proliferation of individual, electrical pump-driven borewells that abstract water from underground aquifers (Sekhar et al. 2006; Javeed et al. 2009). This led to claims of a “democratization of irrigation”, with smallholder farmers accessing irrigation water (Taylor 2013). However, the low productivity of the aquifer (Dewandel et al. 2010; Perrin et al. 2011) and a rapid decline in the groundwater table level led to decreasing borewell yields (Ruiz et al. 2015), implying that (groundwater)-irrigated agriculture still largely depends on rainfall. Climate variability has increased over the last 50 years in this region (Jogesh and Dubash 2014); predictions indicate a 1.8-2.2°C increase in temperature by 2030, and southwestern regions of Karnataka state (southern India) are projected to experience a decrease in annual rainfall, especially during the monsoon season (Jogesh and Dubash 2014). For a region that largely depends on monsoon patterns and winter months to maintain agricultural production, any shift in climate conditions would have a severe impact on natural resources and the economy. Over the past two decades, agrarian India has been in the midst of a considerable crisis, manifested by increasing levels of indebtedness and most tragically exemplified by the wave of farmer suicides that have plagued the countryside of the Deccan Plateau in particular. The need to cope with upcoming debt payments induces farmers to shift towards irrigated cash crops, and gaining control over water access is central to maintain household sustainability. Accessing groundwater may be a solution to provide water for crops on a more regular basis, but this solution must also consider social and cultural aspects of farmer indebtedness, including a new temporal horizon for debt repayment and accounting for the risk of failed wells (Taylor 2013).

In this article, we model adaptive decisions of farmers facing climate change: long-term decisions about investment in borewell irrigation and short-term decisions about cropping systems and the irrigation water application rate for crops. We use a stochastic dynamic model of farmers’ decisions to test socio-economic and water management policies under several climate change scenarios. Various policies are considered (i.e. subsidizing rainfed crops, reforming subsidized energy for irrigation, a water charge indexed to ambient groundwater level), and their impacts on farmer profit and groundwater level are compared. Each scenario is considered along with a climate change scenario to evaluate the potential of each policy to mitigate the climate's impact on groundwater level.

6.2. LITERATURE REVIEW ON LONG-TERM FARMER DECISIONS UNDER UNCERTAINTY

Several fields in the literature have discussed models of farmers' decisions under risk and uncertainty, including irrigation management, ranging from environmental and resource economics to applications of operational research to hydrological issues. Krishnamurthy (2016) presented a theory that clarifies the properties of water management models under risk and uncertainty. Sekhri (2014) explored implications of groundwater irrigation on poverty in rural India using a detailed survey of agricultural wells.

It is essential to consider risk and uncertainty when representing irrigation management and cropping system decisions because of the uncertain nature of water availability for irrigation and crop yield resulting from climate conditions. Iglesias & Garrote (2015) provided a literature review on agricultural adaptation to climate change in Europe that describes the possible drivers of adaptation and policy implications.

Two main approaches are distinguished in the agricultural economics literature (Robert et al. 2016b). First, in stochastic programming, uncertainty and risk are incorporated as non-embedded risk into the objective function, i.e., in prices, yields and revenues, or in constraints, to represent stochastic resource availability (McCarl et al. 1999; Briner and Finger 2013; Graveline 2016). Second, in discrete stochastic programming, uncertainty and risk are incorporated as embedded risks, including both risk anticipation and adjustments, which allows for recourse in the decision.

In stochastic programming, the main advantage of incorporating risk is to consider stochastic variables such as prices, yields, borewell recharge and water availability for irrigation, which are all related to uncertain weather. In this way, relationships between farm production variables and climate are better considered and represented in models. Fernandez et al. (2016) used stochastic programming to model economic impacts of changes in water availability in small-scale agriculture in the Vergara River Basin, Chile. They applied a calibration method for risk programming models with mean-variance model specification developed by Petsakos & Rozakis (2015) to include risk in the objective function of agricultural models. Blanco-Gutierrez et al. (2013) used a risk-based economic optimization model and a hydrologic water management simulation model to model a vulnerable drought-prone agro-ecological area in the Middle Guadiana River Basin, Spain. Similarly, Foster et al. (2014) predicted optimal irrigation strategies under variable levels of groundwater supply for irrigated maize production in the Texas High Plains region of the United States, and assessed the limits of existing models for predicting farmers' land and groundwater use decisions.

In discrete stochastic programming, the decision problem is broken down into several decision stages in which new information is available. It can be represented by decision trees. The typical case treated with discrete stochastic programming is cropping pattern planning under weather and/or water uncertainty. For instance, McCarl et al. (1999), Mejías et al. (2004) and Connor et al. (2009) defined an initial stage that models the choice of long-term capital investments that remain fixed for several years regardless of annual stochastic variations (water allocation and water price). The second stage addresses short-term (annual) decisions, such as water application rates and land for crops or fallow.

The use of dynamic programming to represent and solve water, nutrient or animal feed management problems in agriculture has a long history. Burt (1993) considered an expected present value problem and from dynamic programming generated a set of sequential decision rules for optimal feed rations and marketed animal weights. Randomness in input and output prices was considered, and properties of the stochastic model were examined for two cases of model application: infinite sequence and single batch. However, no empirical application was presented. Bryant et al. (1993) used a dynamic programming model to explore allocation of irrigation among crops under random climate conditions. During dry periods, a crop can be abandoned temporarily or permanently. Intra-seasonal irrigation rules were considered for maize and sorghum in the Texas High Plains. These authors also used a crop simulator to "simplify" decision rules for crop choice and irrigation application rates. Only two plots of fixed size were set, and a fixed irrigation volume was allocated to only one crop.

Ritten et al. (2010) developed a stochastic dynamic programming model for purposes similar to those of Burt (1993), i.e., to solve for optimal stocking rates under climate change. More precisely, they considered farmers' decisions when rainfall is unknown before the start of the growing season. Farmers maximized the current net value of their land, and the (random) dynamic state variable was vegetation density. When climate scenarios were introduced profitability decreased as rainfall variability increased compared to the baseline climate.

Maatman et al. (2002) also considered a stochastic programming model to represent farmers' sequential decisions in response to changes in expected rainfall and introduced a food security condition into the problem. More precisely, the farmer's objective was to minimize nutrient deficits at the household level and during several periods (i.e. beginning of the growing season, later in the the growing season and after harvesting). They presented one of the first examples in the literature of application of stochastic programming with an explicit subsistence strategy for farmers and adaptation to climate change in an intra-seasonal setting. The method, two-stage stochastic models and multiple-recourse models differed, however, from nonlinear stochastic dynamic programming, and no investment decisions in irrigation were considered.

In the present article, we combine several features of the models discussed above into a model that describes farmer decision rules for groundwater irrigation in more detail, with southern India as an empirical application. Specifically, we consider climate scenarios allowing for changes in rainfall distribution and farmer long-term decisions about investment in irrigation, short-term intra-seasonal decisions about crops and plot size, and water application rates. We developed a dynamic stochastic programming model to study these multiple decisions and improve description of the variety of adaptation pathways to climate change.

6.3. METHODS

6.3.1. The farmer's production problem

We consider a representative farmer who makes decisions about irrigation and crop choice, and considers consequences of his current decisions on future water availability (because the latter ultimately determines future crop output, hence future profits). Our framework is based on a bio-economic model with season-specific crop choice and an annual investment decision about irrigation strategies.

The multiple stages of the farmer decision-making process are described as follows:

- At the beginning of the planning horizon, the farmer forms an expectation about several random variables: future climate, future market prices for crops and groundwater availability (for irrigation).
- At the beginning of the year, the farmer decides whether or not to invest in irrigation, or to rely on rainfall for the coming year.
- At the beginning of each growing season, the farmer decides which crops to grow on the farm and the associated land area for each plot (plot size varies).
- For each growing season, the farmer decides the irrigation-water application rate for each crop, given total water availability and observed rainfall.
- For each growing season, given the irrigation equipment and selected crops, the farmer follows a set of irrigation rules to obtain the "best" crop yield, conditional on actual climate conditions. Given the irrigation equipment, selected crops and irrigation practices, the farmer selects the plot size so the most profitable crop is grown on a larger area than less profitable crops. In particular, when a dry climate is expected, farmers are likely to grow multiple crops to diversify the risk of crop failure.

The farmer's objective is to select the sequence of investment in irrigation equipment and season-specific crops that maximize the discounted stream of future revenue across the planning horizon based on expectations on rainfall, available water for irrigation, crop prices, crop costs, crop yields and crop failure.

Farmers maximize seasonal profit as a function of crop choice, plot size and water application rate for each crop (which is a percentage of total available water). Once investment in irrigation and crop choice decisions are made, water input for crops is determined by combining irrigation from groundwater and rainfall. More precisely, water availability (from expected rainfall and expected groundwater level) triggers the decision to grow particular crops and, during the agricultural season, farmers adjust water for plant needs on a daily (or weekly) basis. The adjustment is made according to agronomic "rules", and input or output prices and other economic variables are assumed not to influence these decisions. However, the marginal cost of irrigation water may still depend upon the amount of water abstracted (excluding irrigation investment cost). The farmer makes decisions about crop allocation and irrigation investment, which makes the problem fully dynamic because today's investment decisions will affect water availability in the future. We denote the planning horizon by *T* (years).

Formal representation of the problem is as follows. The representative farmer has *B* plots, on which *C* crops can be planted. Crops can be grown during two cropping seasons (the season index is τ, *with* $\tau = S_1, S_2$) of duration $Season1_{length}$ and $Season2_{length}$, respectively. Farmer decisions depend on, among other things, expected rainfall, which is distributed according to a discrete distribution of five profiles (poor, below average, average, above average or good). Each rainfall regime is associated with an average, season-specific rainfall level denoted $rain_{S1}$ and $rain_{S2}$, respectively, and the probability of occurrence of each rainfall regime at the beginning of each year is denoted pr_{S1} and pr_{S2}, respectively.

The farmer's annual decisions about investment in irrigation include the decision to drill a new borewell, the well's depth ($WELL_{depth}$) and the power of the (electrical) pump (*HP*). Assuming the farmer benefits from a *m*-year loan with a fixed interest rate of *r*%, the annual investment cost is

$$I_t = (1+r)\left(\frac{1}{m}\right)(COST_{well} + COST_{pump}) + COST_{maintenance}, \quad (1)$$

where $COST_{well}$, $COST_{pump}$ and $COST_{maintenance}$ are the costs of borewell construction, purchasing the electrical pump and annual borewell maintenance, respectively.

In hard rock aquifers, drilling a borewell is risky because of possible failure when the borewell does not reach a water fissure. $FAIL_{well}$ denotes the probability of borewell failure (implying that investment in borewell irrigation may well exceed the construction cost of a single borewell); the actual construction cost for an operating borewell ($COST_{well}$) is inflated by $FAIL_{well}$ and is a function of borewell depth ($WELL_{depth}$).

The irrigation capacity of the farm also depends on the depth of the groundwater table (WT_{depth}) and the time available for pumping (hours of electricity available per day in the first season, $Power\_day_{S1}$, and the second season, $Power\_day_{S2}$). The flow rate (FR) of the well provides the maximum water abstraction capacity of the irrigation system and is defined as follows:

$$FR = h(HP, WT_{depth}, WELL_{depth}) \begin{array}{c} > 0 \text{ if } WELL_{depth} > WT_{depth}, \\ 0 \text{ otherwise.} \end{array} \quad (2)$$

The flow rate is considered the state variable of our dynamic model, in which it is denoted W. W is both dynamic and stochastic because it depends on borewell yield, the rainfall recharge factor and depreciation of irrigation capital stock (with a factor of $RATE_{depreciation}$).

The expected water available for irrigation in the first and second seasons ($\overline{W}_{S1}$ and $\overline{W}_{S2}$) is determined from the flow rate, daily power supply available for pumping ($Power\_day_{S1}$ and $Power\_day_{S2}$) and the number of days per season ($Season1_{length}$ and $Season2_{length}$):

$$\overline{W}_{S1} = W \times Power\_day_{S1} \times Season1_{length}$$

and $\overline{W}_{S2} = W \times Power\_day_{S2} \times Season2_{length}$ (3)

Therefore, total irrigation capacity expected for the year is $\overline{W} = \overline{W}_{S1} + \overline{W}_{S2}$ and is distributed among plots according to a season-specific vector $RATE_{irrigation}$. The cost of pumping groundwater to irrigate crops ($COST_{pumping}$) depends on the number of hours of pumping ($HOURS_{irrigation}$), the electric power used ($POWER_{irrigation}$) and the cost of electricity ($COST_{electricity}$):

$$COST_{pumping} = HOURS_{irrigation} \times POWER_{irrigation} \times COST_{electricity}, \quad (4)$$

Where $HOURS_{irrigation} = (Power\_day_{S1} \times Season1_{length} + Power\_day_{S2} \times Season2_{length}) \times RATE_{irrigation}$.

Regarding the choice of the cropping system and irrigation practices, crops can be irrigated or rainfed or both, may be grown during both seasons or only during the monsoon season and can be short-term (only one season) or long-term (over two seasons) crops. When selecting crops, the farmer estimates the chance of crop failure ($RATE_{failure}$) and plans to grow another crop (*c_replace*) if the first crop fails. For a given irrigation capital stock, crop choice and irrigation practices are decided by comparing crop-specific and season-specific expected profits, with the expectation considered among the five rainfall regimes mentioned previously. $\pi_{bc\tau}$.denotes expected profit from crop *c* in season τ on plot *b*, and we approximate $\pi_{bc\tau}$ as:

$$\pi_{bc\tau} \cong \sum_{i=1}^{5} pr_{\tau,i}[\,(1 - RATE_{failure})[PRICE_{c\tau}(\tilde{R}_\tau)YIELD_{bc\tau}(\tilde{R}_\tau, W_{bc\tau}) \times SIZE_{plot} - COST_c - COST_{pumping}]$$

$$+ \left(RATE_{failure}\right) \begin{bmatrix} PRICE_{c_{replace},\tau}(\tilde{R}_\tau) YIELD_{b,c_{replace},\tau}\left(\tilde{R}_\tau, W_{b,c_{replace},\tau}\right) SIZE_{plot} - COST_{c_{replace}} \\ -COST_c - COST_{pumping} \end{bmatrix}, \quad (5)$$

where $\tilde{R}_\tau$ denotes random rainfall in season τ, crop yield ($YIELD_{bc\tau}$) and crop price ($PRICE_{c\tau}$) are stochastic variables that depend on rainfall, $W_{bc\tau}$ is irrigation water applied to crop *c*, and $SIZE_{plot}$ is the size of the plot (fixed or adjusted by the farmer). Because we focus on irrigation, we consider other crop management practices (e.g. fertilizer, seed, labor) as constant; thus, crop cost $COST_c$ is a fixed parameter. Expected profit among rainfall regimes is approximated as the average profit earned during the five rainfall regimes, weighted by their probabilities of occurrence at the beginning of each year (vectors pr_K and pr_R). We assume crop yield is a quadratic function of irrigation water distributed to the crop, which is the minimum between total available water for the crop ($RATE_{irrigation} \times \overline{W}_{S1}$ for the first season and $RATE_{irrigation} \times \overline{W}_{S2}$ for the second season) and the optimal amount of water the crop needs to reach optimal yield ($Irri_c$).

For crop *c* (dropping indexes *b* and τ for the sake of simplicity):

$$YIELD_c\left(\tilde{R}, W\right) = a_c + b_c \min\left[\left(RATE_{irrigation,c}\left(\tilde{R}\right) \times \overline{W}_{S1}, Irri_c\left(\tilde{R}\right)\right]\right.$$

$$+ d_c \min\left[RATE_{irrigation,c}\left(\tilde{R}\right) \times \overline{W}_{S1}, Irri_c\left(\tilde{R}\right)\right]^2, \quad (6)$$

where $RATE_{irrigation,c} \in [0,1], \forall c, c = 1, \ldots, C$.

Because crop price in local markets is likely to depend on climate conditions beyond the farmer's control (because farmers are "price takers"), we assume that crop price is determined from a reference price (REF_c) multiplied by crop price elasticity with respect to rainfall. Hence, price decreases by a factor of α when rainfall shifts to the next rainfall regime, and the random price for crop *c* under rainfall regime $i, i = 1, \ldots, 5$ is

$$PRICE_c = REF_c \times \alpha_i. \quad (7)$$

The farmer's problem over the *T* years of the planning horizon is

$$\max_{\{I_t\}} \sum_{t=1}^{T} (1+r)^{-t} \left\{\max_{\{\delta_{bc\tau}\}} \left[\sum_{b=1}^{B} \sum_{c=1}^{C} \sum_{\tau=S1}^{S2} \delta_{bc\tau}\, \pi_{bc\tau}\right] - I_t\right\}, \quad (8)$$

where *r* is a constant discount rate, and $\delta_{bc\tau} = 1$ if crop *c* is grown on plot *b* in season τ (otherwise 0). We assume that since no a priori condition is imposed on the terminal level of water availability or irrigation capital stock, we have an infinite-horizon problem. To solve this stochastic dynamic programming problem, the Bellman approach is commonly used in the literature (Bertsekas 2011). To simplify notation, we denote $\pi_t^*(I_t, W_t)$ as the profit obtained in year *t* from optimal control variables for problem (8), with year-dependent state variable W_t and control variable I_t. Note that optimal control variables that are season-specific, i.e., crop choice, irrigation application rate and plot size, are implicitly assumed with this notation. The maximization problem is thus equivalently expressed as the following Bellman equation for time period *t*:

$$V(W_t) = \max_{I_t}\{\pi_t^*(I_t, W_t) + \beta\ E_{\tilde{R}}V(W_{t+1})\}, \forall t, \quad (9)$$

where $V(W_t)$ is the value function (the maximum of current and future revenues) with the state variable as its argument, whose (dynamic) transition equation is

$$W_{t+1} = f(W_t, I_t), \quad (10)$$

β is a discount factor and $\pi_t^*(I_t, W_t)$ is the current year's profit function.

A popular way of solving such infinite-horizon problems is a colocation method (e.g., Bertsekas (2011) and Miranda & Fackler (2004)) applied to Equation (9). The unknown value function is approximated through contraction mapping involving Chebyshev polynomials whose associated coefficients are solved iteratively from a value-function colocation technique. If the order of Chebyshev polynomials for approximating the value function is *p*, we form the following system of *p* equations with *p* unknowns evaluated for a given value of the state variable, W_p:

$$\sum_{p=1}^{P} c_p \Phi_p(W_p) = \max\{\pi^*(I, W_p) + \ \beta E_{\tilde{R}} \sum_{p=1}^{P} c_p \Phi_p[f(W_p)]\}, p = 1, \dots, P, \quad (11)$$

where Φ_p and c_p is the Chebyshev polynomial of order *p* and its associated coefficient (to be evaluated), respectively. In the system above, we drop reference to a particular sequence of years (*t* and *t+1*) because we are looking to approximate the value function at the steady state. For this reason, the maximization problem is considered for any pair of subsequent values of the state variable, W_p and $W' = f(W_p)$. The algorithm for solving the problem above starts by selecting a series of *p* approximation points (the Chebyshev nodes) for which optimal controls are calculated. Given optimal values of the control variables, the Chebyshev coefficients are updated in an intermediate stage, and the process continues until convergence in both optimal control values and Chebyshev coefficients.

6.3.2. Data

The model is applied to a representative farmer from the Berambadi watershed in Karnataka, India, who specializes in arable crops, with turmeric, sunflower, marigold, sorghum and maize as major crops grown on two plots. The Berambadi watershed (84 km²) belongs to the Kabini River Basin, which is part of the South Gundal River Basin (816 km²) (southwestern Karnataka). Its climate is dominated by a monsoon regime that generates a strong rainfall gradient with decadal trends, strong inter-annual variability and recurrent droughts (Ruiz et al. 2015). Three seasons regulate the farm cropping system: i) kharif (June to September), the rainy season (monsoon), when most of the cropping area is cultivated; ii) rabi (October to January), the winter season, when most irrigated plots are cultivated; and iii) summer (February to May), the hot and dry season without cultivation.

During kharif, farmers cultivate sunflower, marigold, and maize in rainfed or irrigated conditions and sorghum in rainfed conditions. They also plant irrigated turmeric during this season and harvest it at the end of the next season (rabi). During rabi, farmers grow irrigated maize. If a crop fails during kharif, farmers try to grow maize as a replacement crop to ensure a minimum revenue for the season.

The hard rock aquifer is composed of fissured granite underlain by a 5-20 meter layer of weathered material. In these conditions, using pumps with more horse power is not a solution to increase the amount of irrigation water, due to the low lateral recharge rate, nor is drilling deeper borewells, since this depends on the structure of the fissured granite. In the Berambadi watershed, electricity for irrigation is fully subsidized except for an annual fixed charge of approximately 330 Rs per horse power. Therefore, the marginal cost of power supply for irrigation can be considered 0, even though there are some maintenance costs (discussed above).

Most data were collected from farmer surveys, while some variables were quantified using values from official Indian reports. We surveyed farmers in the watershed in 2014 and 2015. The first survey targeted 27 farmers to obtain detailed data about their practices, in particular their decisions and the process of adapting their decisions. The second survey targeted 680 farmers and obtained general data about farm characteristics and farmers' social, economic and agronomic environment. Data from this survey were used to generate a typology of farmers on the watershed based on biophysical factors (e.g. farm location, soil type, ground water accessibility), economic factors (e.g. farm size, labor, equipment), and social factors (e.g. caste, family structure, education, off-farm employment). Additionally, 52 experimental plots were monitored over three years, which provided observed quantitative data about crop production and management. These data supplemented the verbal information farmers provided during surveys. Meteorological data were obtained from a meteorological station and water gauges installed on the watershed. Prices and costs were obtained from farmers and from official district data from the Indian Ministry of Agriculture and Cooperation (Directorate of Economics and Statistics) and the National Informatics Center (Agricultural Census Division). Several values from the surveys were used to calibrate model parameters (Table 1).

6.4. SIMULATIONS AND RESULTS

6.4.1. Scenarios

To evaluate impacts of scenarios of changes in climate and water management policies on farmers' decisions at the farm scale, several simulations are performed over a planning horizon of 30 years (assumed to be the average lifetime of a borewell).

Baseline scenario

In the baseline scenario, parameters describing the climate, crop marketing conditions (prices and costs) and water pumping conditions (hours of electricity, cost of pumping) are set to average values obtained from farmer surveys.

Climate change scenarios

Scenario 1 describes the cropping system under climate change conditions in which drier weather (less rainfall) would occur more often. We introduce three additional parameters: 1) $shift_{PERC}$ describes the additional weight associated with the rain regimes, in percentage; 2) $shift_{TYPE}$ indicates more weight on the drier rain regimes when it is equal to two or on the wetter rain regimes when it is equal to one; and 3) $shift_{OCCU}$ indicates more weight on the first two rain regimes of a given type when it is equal to 2 or to the first rain regime when it is equal to 1. In all climate change scenarios, we assumed that the proportions of both low and below-average rain regimes would increase by 1% each year (and the proportions of the other rain regimes would decrease by (1-[(*pr*(poor)*1.01)+*pr*(below average)*1.01)])/(*pr*(average)+*pr*(above average)+*pr*(good)). This would increase the chance of drier rain regimes by 30% after 30 years of simulation (Table 2).

Water management policy scenario: subsidized rainfed crops

Scenario 2 describes the cropping system under climate change conditions and a water management policy that aims to limit groundwater abstraction by encouraging farmers to grow crops under rainfed conditions. The policy provides a subsidy to farmers for each unit of land managed under rainfed conditions. Seven levels of subsidies $rainfed_{SUBS}$ are tested every 1000 Rs/ha from 1000-7000 Rs/ha, associated only with rainfed crops (Table 2).

Water management policy scenario: subsidized energy supply

Scenario 3 describes the cropping system under climate change conditions and a water management policy which aims to limit groundwater abstraction by establishing a user fee for supplying electricity to farmers. The policy sets a user fee for electricity for agricultural purposes. Five levels of fee $electricity_{FEE}$ are tested every 0.50 Rs/kWh from 0.50-3.50 Rs/kWh (Table 2).

Water management policy scenario: water charge based on groundwater level

Scenario 4 describes the cropping system under climate change conditions and a water management policy that aims to limit groundwater abstraction by establishing an ambient tax on farmers (Segerson 1988; Graveline 2013) based on groundwater level. The policy specifies an ambient water charge based on measured groundwater level, and all farmers located on the same aquifer will have the same tax, regardless of their individual water abstraction. Groundwater level is impacted by total water use of the shared aquifer. The annual tax is applicable when groundwater level has decreased by more than 10% from its initial depth (at the beginning of the planning horizon) and has decreased between the beginning and the end of the given year. In these conditions, the ambient tax WT_{TAX} is proportional to groundwater depletion when the latter exceeds $WT_{DECREASE}$ = 10%. Nine tax levels are tested every 100 Rs/% from 200-1000 Rs/% (Table 2).

6.4.2. Results

The dynamic stochastic problem program described in Equation (11) is solved with *p=10* as the order of Chebychev polynomials and approximation nodes. The convolution converged in 111 iterations and took 64 minutes and 47 seconds on a 2 GHz desktop computer. The criterion for convergence is that the sum of squared errors between polynomial coefficients of two consecutive iterations must be less than 0.0001.

The simulation results depend greatly on the validity and quality of the input assumptions and data. The model's predictions should be considered more as trends rather than absolute values.

Baseline scenario

Under the baseline scenario (Figure 6.1), the farmer invests in a borewell during the first year of simulation. Investing in a borewell allows him to switch from rainfed marigold to irrigated sunflower and turmeric in kharif and from rainfed maize to irrigated maize in rabi. The total amount of pumped water allowed by the borewell flow rate is used each year. The deeper the groundwater table, the lower the pump flow, which requires the farmer to reconsider plot and water allocation between sunflower and turmeric. In the 19^{th} year, the water in the first borewell becomes extremely low due to the low flow rate, and the farmer has to decrease the area of turmeric in favor of sunflower, which decreases profits. The first borewell becomes dry after 20 years of pumping. To maintain this irrigated system, the farmer has no choice but to invest in a second borewell, deeper than the first, at the beginning of the 21^{st} year. Groundwater level decreases from 60 to 116 m.b.g.l. during the planning horizon. Increasing groundwater depth by 56 m over 30 years is an extremely severe scenario.

Scenario1 : Climate change scenario

Under the climate change scenario, the farmer's investment behavior is similar to that in the baseline scenario, except that the first borewell becomes dry at the end of the 19th year of pumping, prompting the farmer to drill a second borewell in the 20th year (one year earlier than in the baseline scenario) (Figure 6.2). The 20th year is disastrous for the farmer because his first borewell is dry and he still has one year of loan repayment left for it, in addition to the new loan obtained for the second borewell. With a higher probability of a dry weather, expected groundwater recharge decreases, prompting the farmer to reduce the area of turmeric in favor of sunflower earlier than in the baseline scenario. Profits are thus lower in this scenario. The groundwater level decreases from 60 to 118 m.b.g.l. during the planning horizon. As in the baseline case, increasing groundwater depth by 58 m over 30 years is an extremely severe scenario.

Scenario2: Climate change and subsidized rainfed crops

For subsidies up to 3000 Rs/ha, farmer behavior is similar to that in the climate change scenario without a water management policy (Figure 6.3). The farmer invests in a borewell the first year to grow irrigated turmeric and sunflower in kharif. In the 19th year, instead of growing both turmeric and sunflower, the farmer grows only irrigated sunflower, providing one additional year of pumping (compared to the climate-change-only scenario) before the borewell dries up. Instead of drilling a second borewell, the farmer benefits from the subsidy by growing rainfed marigold. Receiving the subsidy is more profitable than investing in a new borewell. Annual profit in each of the last ten years ranges from 8400-15,900 Rs/ha with a subsidy of 1000 Rs/ha of rainfed land, compared to 6400-7900 Rs/ha under the climate change scenario without a water management policy. From 4000-6000 Rs/ha, irrigated sunflower is replaced by rainfed marigold. All available water is used on turmeric until the 19th year. From there, water use goes from 70 to 65 percent of available water in kharif but stops in rabi season, corresponding to the volume of water recharge from rainfall in kharif and rabi. As a result, the borewell is not even dry after 30 years of pumping. This scenario leads to a depletion of 40 m of groundwater table height after the 30-year planning horizon. For a subsidy of 7000 Rs/ha of rainfed crops, the farmer postpones the decision to invest in a borewell until the 15th year. In that year, the groundwater table reaches 45 m.b.g.l., with 15 m of recharge from rainfall. The groundwater table is high enough to grow turmeric on three-quarters of the land under optimal cropping conditions, and profit from the crop will cover drilling of the borewell and even ensure extra revenue in the first year of investment. Unfortunately, pumping influences groundwater level faster than recharge from rainfall, and water for irrigation rapidly decreases, pushing the farmer to decrease the area of turmeric. Finally, with a subsidy of 7000 Rs/ha, groundwater depth increases by only 27 m after 30 years, and with a subsidy of 8000 Rs/ha, the farmer does not drill a borewell.

Scenario 3: Climate change and power supply fees

When electricity costs 0.50 Rs/kWh, farmers invest in a borewell the first year to irrigate a cropping system consisting of turmeric and sunflower as much as possible during kharif (Figure 6.4). Pumping at this rate causes the borewell to dry up after 25 years, after which the farmer grows only sunflower and pumps only an amount of water equal to the recharge from rainfall. When electricity costs 1.00-1.50 Rs/kWh, farmers drill borewells in the first year and grow maize during rabi under rainfed conditions to use all water during kharif for turmeric and sunflower. At 2.00 Rs/kWh, farmer behavior is similar to that at 1.00-1.50 Rs/kWh, except farmers begin to grow only sunflower in the 19th year and only irrigate as much as the recharge to maintain the borewell level at 82 m.b.g.l. From 2.50 Rs/kWh, farmers delay investing in a borewell, which leads to groundwater table recharge from rainfall. At 2.50 Rs/kWh, a borewell is drilled in the 6th year, and the groundwater level is maintained at 66 m.b.g.l. from the 14th year, with the farmer growing only sunflower with an amount of water equal to the recharge from rainfall. At 3.00 Rs/kWh, a borewell is drilled in the 14th year, and the groundwater level is maintained at 48 m.b.g.l. from the 18th year. At 3.50 Rs/kWh, the borewell is dug in the 21st year, and the groundwater level is maintained at 36 m.b.g.l.

Electricity cost influences profit greatly as soon as farmers invest in a borewell. Farmers first stop irrigating during rabi and then begin to decrease irrigation during kharif to use only part of their pumping capacity.

Scenario 4: Climate change and water charge based on groundwater level

Since groundwater level is allowed to decrease slightly, the first decision a famer makes is to drill a borewell in the first year (Figure 6.5). As long as the groundwater level does not fall “too much”, growing irrigated crops is profitable. Once the 10% threshold is reached, the farmer decreases water abstraction until he pumps only the equivalent of recharge from rainfall during kharif,and stops pumping during rabi so that the groundwater level no longer declines. When this occurs, only irrigated sunflower is planted. For instance, with a water tax at 200 Rs per percentage of groundwater depletion below 10%, the farmer will pump from the borewell until it falls to 79 m.b.g.l. in the 9th year, yielding a maximum tax of approximately 4330 Rs/year. After this year, the farmer changes the cropping system from turmeric-sunflower to sunflower-sunflower, irrigating with a volume equal to borewell recharge. At 600 Rs/%, the threshold becomes 70 m.b.g.l. in the 6th year, which yields a maximum tax of 4600 Rs/year. At 1000 Rs/%, the farmer grows only sunflower starting in the 5th year so that water in the borewell does not decrease below 68 m.b.g.l., which yields a maximum tax of 3330 Rs/year.

6.5. DISCUSSION

Uncertainty and risk significantly influence farmers' decisions and should be considered when modeling decision-making processes in farming systems. In agricultural economics, two main modeling approaches treat risk and uncertainty as factors either non-embedded in stochastic programming or embedded in discrete stochastic programming. In the present study, a dynamic stochastic programming model with recursive programming was built to study decisions about investment in borewell irrigation and about cropping systems under climate risk.

The model tested water management policies aiming at limiting groundwater table depletion. Given hypothesis and simplifications used to describe our representative Indian farmer, it showed that under climate change, a tax on the ambient groundwater level could be an appropriate approach to stabilize groundwater level and limit a decline in farmers' profits. Another common policy in watersheds to manage water resources (e.g., the Beauce plain in France (Graveline, 2013)) is an individual quota policy in which farmers pay a fixed charge for any water pumped beyond their initial quota. This approach requires using water meters to monitor the volume of water pumped, which is costly.

This study adds to the literature on irrigation management and agricultural adaptation to climate change in semi-arid countries involving a dynamic bio-economic representation of farmer decisions under climate change in a dynamic setting. First, we consider investment decisions about irrigation over a long-term horizon, which is similar to the horizon for impacts of climate change and therefore relevant. This helps assess expected impacts of specific climate scenarios (average rainfall intensity and rainfall distribution) and benefits of long-term decisions about irrigation infrastructure, while using the same bio-economic decision model for crop choice and irrigation water application rate. Second, we consider several policies that provide farmers with incentives to manage water abstraction in an optimal manner. Third, we combine climate and economic scenarios to explore the robustness of farmer adaptation strategies to changes in the outlook of agricultural markets. Fourth, the description of farmers' water practices (including borewell characteristics and water application rate) is as detailed as the representation of crop choice based on the agricultural season. Most references in the literature focus on only one of these two dimensions. This accurate description of farmer behavior allows us to explore a wider range of adaptation strategies in response to climate or market events. Our decision model encompasses a significant range of possible farmer decisions, especially during agricultural seasons within a year, in a way that better represents options available to Indian farmers for adapting to climate change. Because our representation of agricultural production technology using groundwater irrigation is more detailed than that of most articles in the literature, it is able to capture implications of farmer decisions for revenue and the groundwater level more accurately. More precisely, the flexibility of the production model, in which plot size, crop choice, crop succession and irrigation application rate can be optimized, is expected to provide a more realistic representation of the sensitivity of farmer revenues to market prices and policy instruments. It is well known (e.g., Chavas, 2012) that, according to the Le Chatelier-Samuelson principle, the sensitivity of an agent's decisions to external pressures is higher if more degrees of freedom exist (for instance, more control variables) (Samuelson 1961). In its more popular version, this principle states that elasticity of input demand or output supply is lower in the short-term, when all technological dimensions are fixed, than in the long-term, when decisions can include production technology. When models represent production technology as less flexible than it really is, they are likely to under-estimate sensitivity to prices or policy instruments. For instance, when crop choice and plot size are decision variables, an increase in access cost to irrigation is likely to require more adaptation by the farmer than when crop systems are fixed. Additionally, a farmer may be more sensitive to changes in irrigation cost in the long-term, when irrigation capital becomes a control variable, than in the short-term, when only season-specific decisions are feasible. Representing more decision variables is necessary to better evaluate impacts of changes in market variables and the performance of policy instruments that influence farmers' decisions.

There are several caveats to our analysis. First, the generic nature of the bio-economic and groundwater irrigation model is limited due to the need to calibrate many agricultural and hydrological parameters. Even the representation of irrigation technology is based on hard rock fractured aquifers, and the list of possible crops is also specific to the watershed considered in our case study. The simulations yield solutions that depend greatly on the validity and quality of the input assumptions and data. The model's predictions should be considered more as trends rather than absolute values. However, the structure of the bio-economic model may be used for a wide range of agricultural settings, as long as decisions about crop choice and irrigation are of similar nature, and provided that the model can be calibrated with survey and/or technical data. Second, the model was built to be applicable to other settings and research on investment decisions that influence future decisions about farm management. An important issue regarding farmers' decisions that the model does not address is the importance of subsistence crops. These crops are not grown to be sold but to be consumed by the household. Their cultivation depends on household needs and current stocks of grain. One way to address this limitation is to allocate one plot to a subsistence crop (sorghum), the size of whose plot will be optimized to fill the stock for the coming year. Another possibility is to estimate the cost of buying all subsistence grain at the market to cover family needs and ensure that the farm has enough capital to purchase it each season and each year. Third, we restricted farmers' risk and uncertainty preferences to risk neutrality and non-ambiguity. Farmers are assumed to maximize expected profit based on decision variables in the long- and short-terms, but they are not risk averse and therefore do not adapt production strategies to hedge against production or price risks. Extending our model by considering the expected-utility framework or prospect theory to avoid limitations of the expected-utility framework (e.g., Bocquého, Jacquet, & Reynaud (2013)) is certainly feasible, provided risk preferences can be inferred from field surveys or the literature (Ridier, Chaib, & Roussy, 2016).

6.6. CONCLUSION

We developed an original dynamic stochastic programming model with recursive programming to study decisions about investment in borewell irrigation and about cropping systems under climate risk. We used the model to test socio-economic and water management policies under climate change scenarios. The model was initially developed to address critical issues surrounding groundwater depletion and farming practices in a watershed in southwestern India. Its structure can be used in other agricultural settings.

ACKNOWLEDGEMENTS

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TABLE CAPTION

Table 6.1. Calibration parameters. Information in parentheses describes either the type of input parameter used in the model or its unit.

FARM CHARACTERISTICS		
N_{plot} (int)	Number of plots	2
$SIZE_{farm}$ (double)	farm size (ha)	2.0
SEASON CHARACTERISTIC		
$Season1_{length}$ (double)	Length of the first season (days)	180.0
$Season2_{length}$ (double)	Length of the second season (days)	120.0
RAINFALL REGIMES		
$rain_N$ (int)	Number of rain regimes	5
$rain_{NAME}$ (vector of strings, of dimension $rain_N$)	Name of the rain regimen	Poor
		Below average
		Average
		Above average
		Good
$rain_{CODE}$ (vector of integer, of dimension $rain_N$)	Code of rain regimes	1
		2
		3
		4
		5
$rain_{S1}$ (vector of double, of dimension $rain_N$)	Rainfall in the first season (mm)	560.5
		624.62
		784.33
		859.6
		934.6
$rain_{S2}$ (vector of double, of dimension $rain_N$)	Rainfall in the second season (mm)	297.82
		354.55
		427.19
		558.0
		635.50
pr_{S1} (vector of double, of dimension $rain_N$)	Proportions of rain regimes in the first season	0.073
		0.220
		0.463
		0.220
		0.024
pr_{S2} (vector of double, of dimension $rain_N$)	Proportions of rain regimes in the second season	0.024
		0.195
		0.512
		0.195
		0.073

WELL CHARACTERISTICS		
$WELL_N$ (int)	Number of cases for $WELL_{depth}$	3
$WELL_{depth}$ (vector of double, of dimension $WELL_N$)	Depth of borewell (m)	100.0
		150.0
		200.0
WT_{depth} (double)	Ground water depth level (m.b.g.l.)	60.0
$FAIL_{well}$ (double)	Probability of well failure	0.2
$COST_{well}$	Cost of drilling a well (Rs)	dynamic
$RATE_{depreciation}$ (double)	Depreciation rate of irrigation facility	0,95
$COST_{maintenance}$	Maintenance cost (Rs)	dynamic
FR, W, W'	Flow rate (m^3/h)	dynamic
SI (double)	Borewell specific yield	0.021
FR (double)	Rainfall recharge factor	0.054
$\bar{W}$	Total water available (mm/ha)	dynamic
$\bar{W}_{S1}$	Available water the first season (mm/ha)	dynamic
$\bar{W}_{S2}$	Available water the second season (mm/ha)	dynamic
$IRRI_N$ (int)	Number of values for $RATE_{irrigation}$	11
$RATE_{irrigation}$ (vector of double, of dimension $IRRI_N$)	Proportion of available water to plots	0.0
		0,1
		0,2
		0,3
		0,4
		0,5
		0,6
		0,7
		0,8
		0,9
		1
PUMP CHARACTERISTICS		
HP_N (int)	Number of cases for HP	3
HP (vector of double, of dimension HP_N)	Pump horse power (HP)	0.0
		7.0
		14.0
$COST_{pump}$	Pump purchase cost (Rs)	dynamic
$Power\_day_{S1}$ (double)	Power in the first season (h/day)	4.0
$Power\_day_{S2}$ (double)	Power in the second season (h/day)	3.0

CROP CHARACTERISTICS						
$crop_N$ (int)	Number of cases for $crop_{NAME}$	5				
$crop_{NAME}$ (vector of strings, of dimension $crop_N$)	Crop names	Maize				
		Sunflower				
		Sorghum				
		Turmeric				
		Marigold				
$crop_{CODE}$ (int)	Crop codes	1				
		2				
		3				
		4				
		5				
$YIELD_c$	Crop yield (t/ha)	dynamic				
$PRICE_c$	Crop price (Rs/t)	dynamic				
$COST_c$ (vector of double, of dimension $crop_N$)	Crop cost (Rs/ha)	6058.0				
		9642.0				
		1110.0				
		45566.0				
		23584.0				
$RATE_{failure}$ (vector of double, of dimension $crop_N$*$rain_N$)	Crop failure rate	0.50	0.60	0.50	0.80	0.70
		0.30	0.40	0.30	0.50	0.50
		0.15	0.15	0.15	0.15	0.15
		0.10	0.10	0.10	0.10	0.10
		0.05	0.05	0.05	0.05	0.05
REF_c (vector of double, of dimension $crop_N$)	Reference crop prices (Rs/t)	10436.0				
		29190.0				
		10664.0				
		71810.0				
		10000.0				
α	Price elasticity factor	0,1				
T	Planning horizon (years)	30				

Table 6.2: Experimental design for simulations

Control Variables	***Baseline***	***Scenario1***	***Scenario2***	***Scenario3***	***Scenario4***
$shift_{PERC}$	0.0	1%	1%	1%	1%
$shift_{TYPE}$	1	2	2	2	2
$shift_{OCCU}$	1	2	2	2	2
$rain_{SUBS}$	0.0	0.0	[1000-7000 Rs/ha]	0.0	0.0
$electricity_{FEE}$	0.0	0.0	0.0	[0.5-3.5 Rs/kWh]	0.0
$WT_{DECREASE}$	0.0	0.0	0.0	0.0	10%
WT_{TAX}	0.0	0.0	0.0	0.0	[200-1000 Rs/%]

FIGURE CAPTION

Figure 6.1: Baseline scenario over the planning horizon (30 years): A) groundwater level, B) farmer profit and C) relative crop area in kharif (irrigated maize replaces irrigated sunflower in rabi) (blue columns indicate investment years).

Figure 6.2: Climate change scenario: A) groundwater level, B) farmer profit and C) relative crop area in kharif (irrigated maize replaces irrigated sunflower in rabi) (blue columns indicate investment years).

Figure 6.3: Climate change and subsidized rainfed crops scenario: A) groundwater level, B) farmer profit, C) relative crop area in kharif for 7,000 Rs of subsidies D) relative crop area in kharif for 4,000 Rs of subsidies and E) relative crop area in kharif for 1,000 Rs of subsidies (irrigated maize replaces irrigated sunflower in rabi) (blue columns indicate investment years).

Figure 6.4: Climate change and power supply fee scenario: A) groundwater level, B) farmer profit, C) relative crop area in kharif for 3.50 Rs/kWh of fee D) relative crop area in kharif for 2.00 Rs/kWh of fee and E) relative crop area in kharif for 0.50 Rs/kWh of fee (irrigated maize replaces irrigated sunflower in rabi) (blue columns indicate investment years).

Figure 6.5: Climate change and water tax based on groundwater level: A) groundwater level, B) farmer profit, C) relative crop area in kharif for 1000 Rs/% of tax D) relative crop area in kharif for 600 Rs/% of tax and E) relative crop area in kharif for 200 Rs/% of tax (irrigated maize replaces irrigated sunflower in rabi) (blue columns indicate investment years).

A)

B)

C)

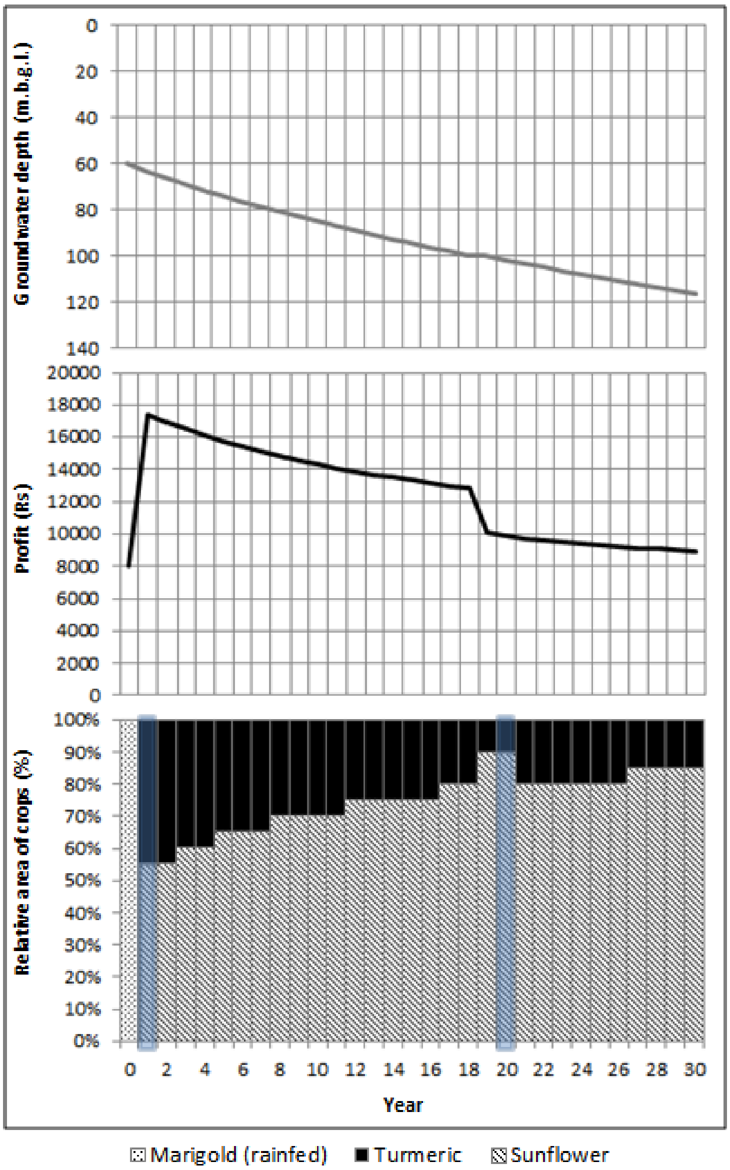


Figure 6.1

A)

B)

C)

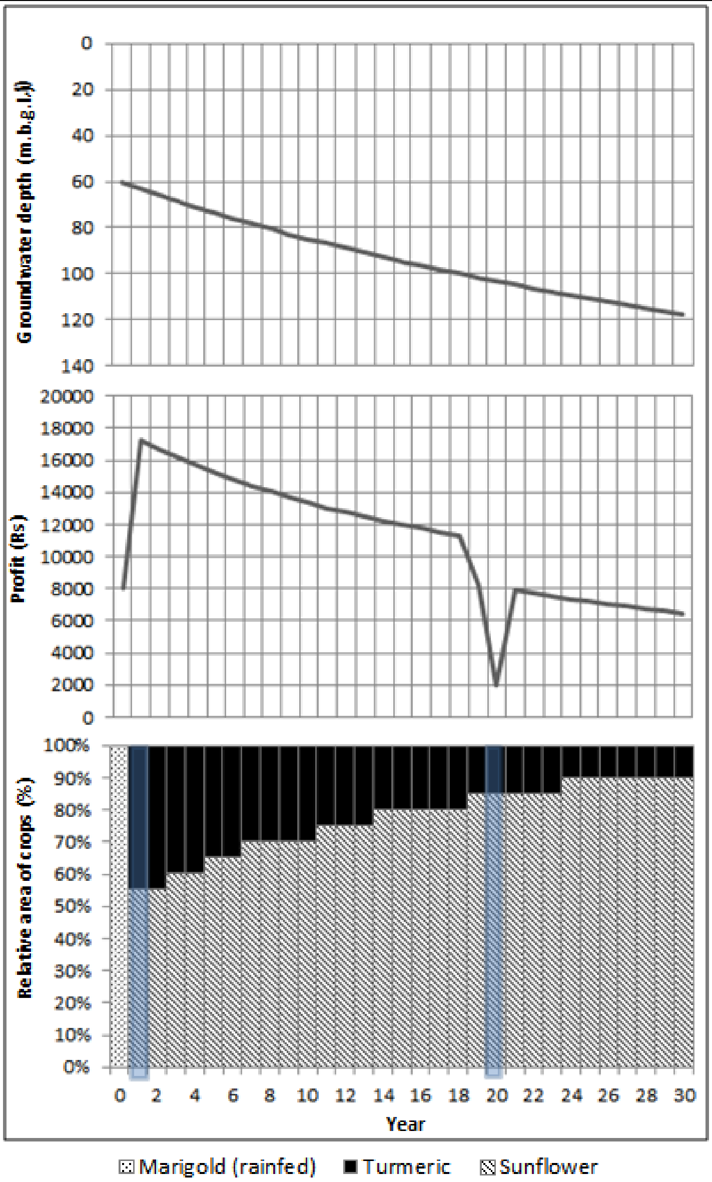


Figure 6.2

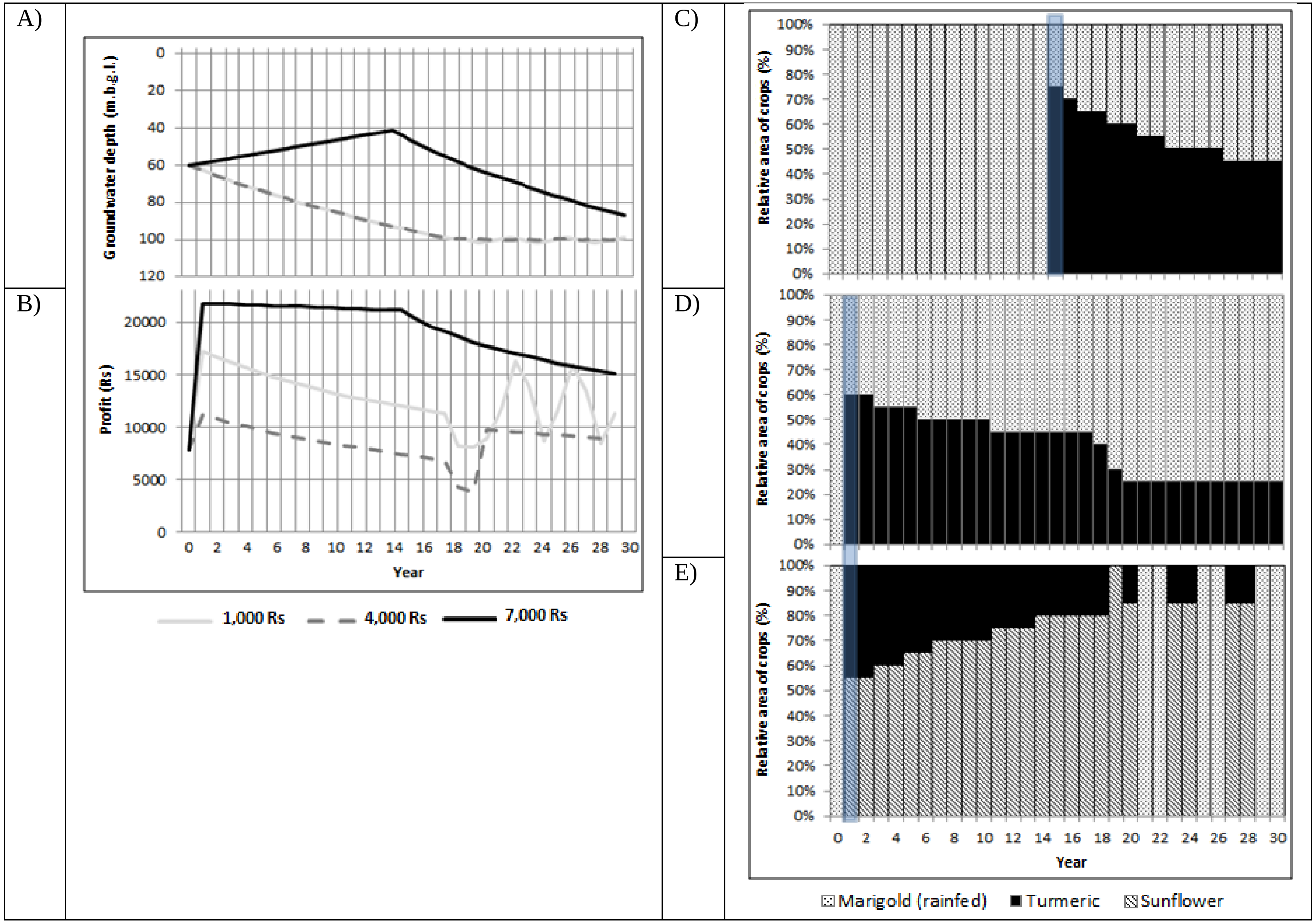

A)
B)
C)
D)
E)
Groundwater depth (m.b.g.l.)
Profit (Rs)
Year
1,000 Rs
4,000 Rs
7,000 Rs
Relative area of crops (%)
Marigold (rainfed)
Turmeric
Sunflower

Figure 6.3

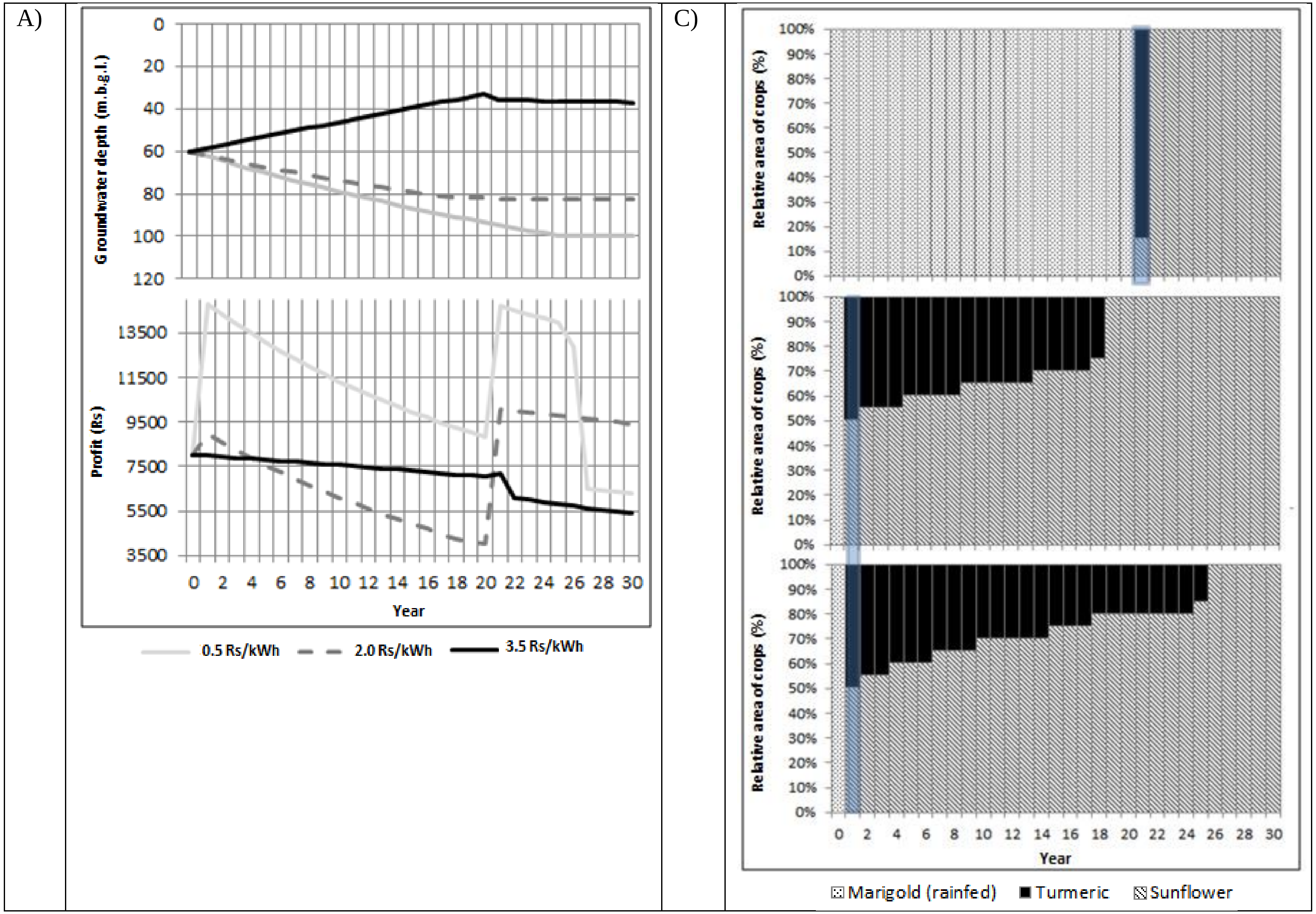
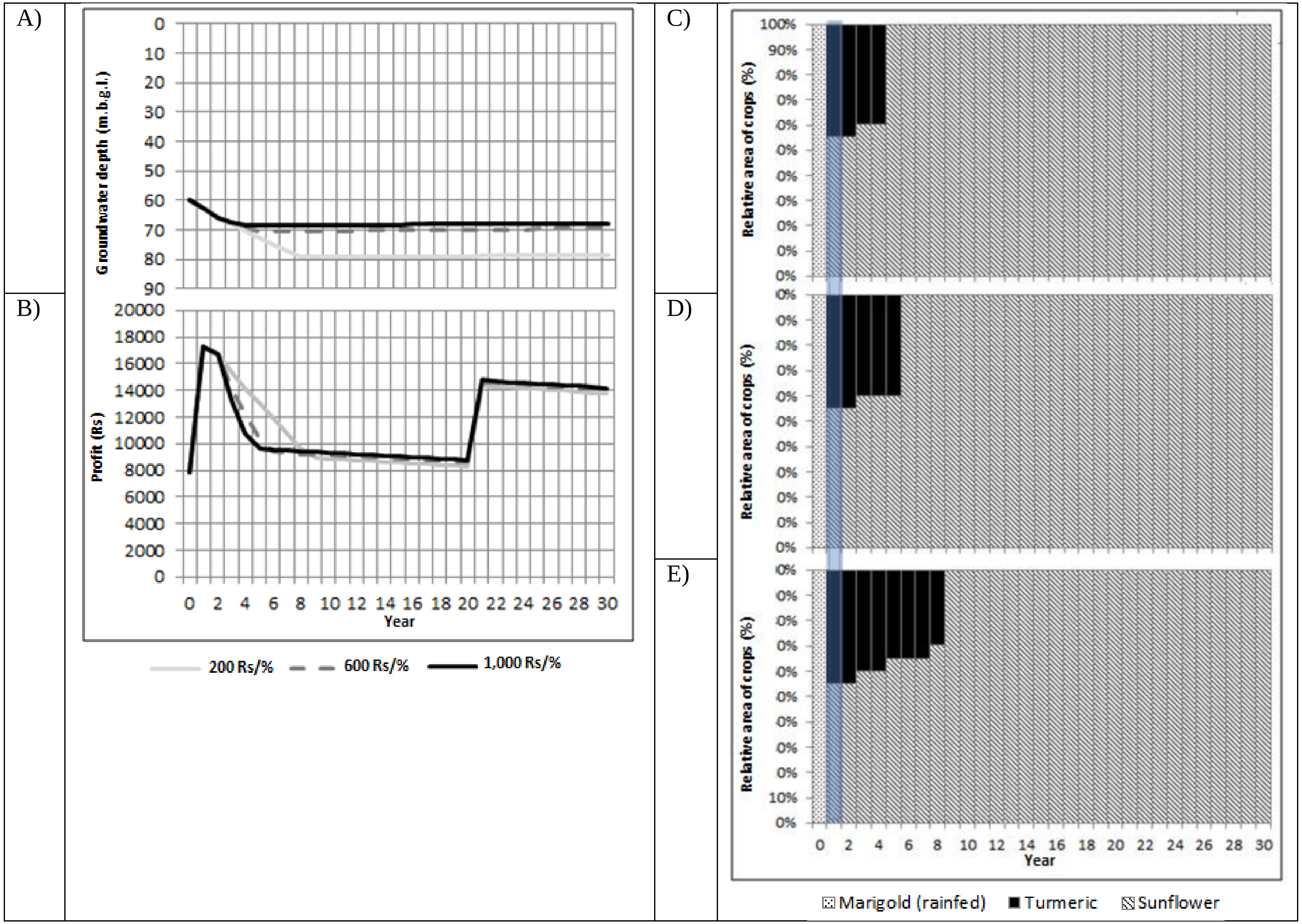

A)
Groundwater depth (m.b.g.l.)
0
20
40
60
80
100
120
Profit (Rs)
13500
11500
9500
7500
5500
3500
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Year
0.5 Rs/kWh
2.0 Rs/kWh
3.5 Rs/kWh
C)
Relative area of crops (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Year
Marigold (rainfed)
Turmeric
Sunflower

Figure 6.4



A)
B)
C)
D)
E)
Groundwater depth (m.b.g.l.)
Profit (Rs)
Year
200 Rs/%
600 Rs/%
1,000 Rs/%
Relative area of crops (%)
Marigold (rainfed)
Turmeric
Sunflower

Figure 6.5

Chapter 7

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

Marion Robert*[1], Alban Thomas[2], Muddu Sekhar[3,4], Hélène Raynal[5], Éric Casellas[5], Pierre Casel[1], Patrick Chabrier[5], Alexandre Joannon[6] and Jacques-Éric Bergez[1]

1 INRA, Université Fédérale de Toulouse, UMR 1248 AGIR, F-31326 Castanet-Tolosan, France
2INRA, Toulouse School of Economics, UMR 1081 LERNA, F-31000 Toulouse, France
3Indian Institute of Sciences, Department of Civil Engineering, Bangalore 560012, India
4Indo-French Cell of Water Sciences, IRD-IISc, Bangalore, India
5INRA, UR 0875 MIAT, F-31326 Castanet-Tolosan, France
6INRA, UR 0980 SAD-PAYSAGE, F-35042 Rennes, France

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* Corresponding author: (marion.robert@inra.fr)

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.

Keywords: farmer's decision-making process, adaptation, modeling, climate change, water management policy

7.1. 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 abstract 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 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 decisions do not provide enough detail about daily management tasks to be operational; 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 (Figure 7.1 7.1) (Akplogan 2013). According to a review of modeling adaptive processes in farmers' decision-making (Robert et al. 2016b), 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 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.

7.2. MATERIALS AND METHODS

7.2.1. Conceptual modelling

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. 2016c) (Figure 7.2 7.2).

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 1987b; 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 of the farming system, 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)).

7.2.2. RECORD: a modeling and simulation computer platform

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 both atomic and coupled models and enables using different temporal and spatial scale 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 between the generic VLE and the framework adapted to the domain of agro-ecosystems. These extensions help modelers in developing their models in the formalism they are used or which is the most suitable (see Bergez et al. (2013) for an extended description of the platform). In this study, two VLE extensions (“Decision” and “DifferenceEquation”) were used to build the model, and a specific package (RVLE) for the statistical software R (R Core Team, 2016) was used to help perform simulations.

VLE extension “Decision”

To represent farmers’ operational decision-making processes, the “Decision” extension (Bergez et al. 2016) implements the “decision” portion of the model in the “decision system/operating system/biophysical system” approach. During simulations, the decision model captures identifies the state of the environment (e.g. weather, plant, soil, resource availability) and sends orders to the connected models (e.g. a biophysical crop model) according to a flexible work plan of activities (i.e. the tasks to be achieved).

The work plan of activities contains the following:

i) a knowledge base composed of information about the system used to reach a decision. The information includes dynamics of biophysical processes, availabilities of human and material resources, and spatial information about farm structure. They are organized as a set of variables whose values evolve during the simulation to update the knowledge base at each time step.
ii) tasks to be executed and associated conditions (predicates, rules and time windows)
iii) temporal relations between tasks (for details of the “Decision” extension, see Bergez et al. (2016))

Recently, resource constraints were added to the conditions associated to the tasks. A set of available discrete resources is defined and structured by categories within the knowledge base. Resource constraints are defined for each task by a needed quantity, possible alternatives and priorities. During simulation, the resource allocation is sequentially managed depending on resource availability and task priorities.

VLE extension "DifferenceEquation"

The VLE extension "DifferenceEquation" extension formulates time-discrete models that calculate values of real variables at time t as a function of the value of variables in the system at time t-Δ, t-2Δ, etc. (e.g. VarX(t+1) = f(VarX(t))). The expected parameters for an atomic model using "DifferenceEquation" are i) the simulation time-step (Δt), which must be the same for all equations; ii) the mode (either "name", in which all external variables share one input port, or "port", in which each external variable has its own input port); and iii) the variables (a list of state variables and their initial values).

RVLE: a user-friendly tool in the RECORD platform

RVLE (www.vle-project.org) is an R package that calls VLE's application-programming interface from R. It can open packages and read model structure (VPZ files), assign experimental conditions to models, call the simulator, build experimental frames and turn simulation results into an R object such as a matrix or dataframe. It is especially useful for analyzing simulation results and performing statistics. It also allows users to manipulate models from the simpler environment of R.

7.3. DESCRIPTION OF THE FARMING SYSTEM MODEL

7.3.1. Models used to build the farming system model

The decision system

3D: three integrated decision models

The novelty of the decision system is that we developed three integrated decision models to represent farmers' strategic, tactical and operational decisions and adaptations. The strategic model simulates farmers' strategic decisions, which include decisions about investment and cropping systems. The tactical model simulates farmers' tactical decisions, especially adaptation of cropping systems. The operational model simulates farmers' operational and crop management decisions.

We used three modeling formalisms to describe farmers' decisions throughout the decision process. Decisions about investment and cropping systems that are influenced by economic return (maximizing profit) were expressed using dynamic stochastic programming. Decisions about establishing cropping systems that are influenced by motivations besides economic return (e.g. proximity to a market, equipment) were implemented via a decision-rule modeling approach using a specific descriptive language whose syntax is based on formal IF-THEN-ELSE rules written as a Boolean condition:

“IF<*indicator*><*operator*><*threshold*> THEN <*action1*> ELSE <*action2*>”. Decisions about crop management were described by a knowledge base and an activity graph supported by the “Decision” extension in the RECORD platform. The knowledge base collects information that the farmer obtains from the biophysical subsystem when monitoring and observing the environment. The activity graph represents the farmer’s work plan and relies on the knowledge base to activate or disable technical operations (Figure 7.3A). An activity denotes a task. Rules control the start of the activity by checking whether conditions necessary to perform the operation exist (Figure 7.3B) (for details of this formalism, see Bergez et al. (2016)).

Modeling resource management in the operational decision model

From a modeling viewpoint, two types of resources were distinguished in the farming system: i) conditional, discrete and returnable resources, which are necessary to execute an operation and can be used and then returned once the operation is finished (e.g. labor, tractor); and ii) unconditional and consumable resources, which are not necessary to execute an operation and are consumed and not returned after use in an operation (e.g. irrigation water). These resources are managed differently in the model. The operating system manages the unconditional and consumable resources. For example, following an order to execute irrigation, the decision system returns each day the amount of water needed to irrigate the farm. The operating system compares the water needed to the water available and executes the order to irrigate by transferring the larger of the two values (water needed or water available) to the biophysical system.

Conflicts between activities requiring the same resources at the same time are dynamically managed using rules to allocate resources and determine the order in which activities are executed. Prioritization is managed by rules that temporally rank activities that can be executed simultaneously. Ranks can be reviewed and updated by other rules.

The operating system

The operating system translates decision orders into executable and timed actions. It calculates the duration of each activity based on the quantity and type of resources that an operation uses and the speed with which each resource executes an operation (entered in the experimental conditions of the simulation). The operating system can also transform certain data transferred from the decision system so that data units correspond to those expected by the receiving model. The operating system is implemented using difference equations in RECORD.

The biophysical model

The STICS model, which represents the crop and soil system, simulates dynamics of a crop-soil system over one or more crop cycles at a daily time-step (Brisson et al. 1998). We selected STICS for its adaptability to many crop types, robustness in a wide range of soil and climate conditions and modularity (Brisson et al. 2003). It has been successfully used in spatially explicit applications and coupled with hydrological models at the watershed level (Beaujouan et al. 2001). STICS receives the crop operations and parameters applied to the plot from the operating system, which executes orders provided by the decision system. STICS returns information about crop stage, yield, soil characteristics, water use and drainage. The FORTRAN code in STICS was wrapped into an atomic model using difference equations in RECORD (Bergez et al. 2014).

7.3.2. Model structure

The model is composed of one decision system and one operating system, the latter of which interacts with one biophysical system (Figure 7.2). The biophysical system can be made up of several crop models. For example, an independent STICS model represents the crop and soil of each plot of the modeled farm. For each plot, the decision system has a work plan with specific activities listed for the plot’s crop. Several work plans may run in parallel when the modeled farm has several plots.

The resource manager must manage conditional, discrete and returnable resources both among activities in a given work plan and among work plans. In this case, prioritization is used to rank all activities temporally. Unconditional and consumable resources are distributed by an intermediary model that, for example, allocates irrigation water to plots when the decision system sends several irrigation orders on the same day. Available water is distributed according to priorities assigned to work plans. To simulate the cropping system over several years, several work plans for the same plot must be run sequentially; the next one is loaded when the last activity of a given work plan is completed.

7.3.3. Dynamic functioning

In systemic modeling, models must be able to interact with each other to provide feedback and other types of interactions. Two types of variables are identified in models: state variables, which are managed by the model itself, and external variables, which are managed by other models.

The sequence diagram (Figure 7.4) illustrates the event flow and communications established between models for systemic modeling of a farming system. Strategic decisions are made once a year at the beginning of the calendar year, while tactical decisions are made at the beginning of each cropping season. Operational decisions are made daily, and return events occur only when operation orders are effective. In this example, we considered two cropping seasons (days 100-250 and 251-355) and two operations (sowing on day 130 and harvest on day 240. External events (e.g. rainfall, market prices, electricity availability) and availability of resources (e.g. labor, equipment, irrigation water) are summarized in the INPUTS model (Figure 7.4).

At the beginning of the year, the strategic model receives information from INPUTS so that strategic decisions about investment and long-term cropping systems are based on farmers' knowledge and objectives. These two types of strategic decisions are forwarded to the tactical and operational models, respectively. At the beginning of the cropping season, the tactical model receives information from INPUTS so that farmers' knowledge is updated. This new information prompts the tactical model to update the cropping system and forward the adapted cropping system to the operational model. At the operational level, decisions are based on the appropriate agronomic context and the farmers' updated knowledge. Once both types of information meet the requirements for executing an operation and are forwarded to the operational model, an operation order (sowing on day 130) is transferred to the operating system, which translates it into a task execution so that the operation is performed in the plot one day after the decision is made (day 131). At the end of the operation, the crop model returns the agronomic context to the operational model. The same process occurs for the second activity, harvest, on day 240. After harvest, the operational model informs the tactical model that the cropping season is over. When the tactical model automatically wakes up on day 250 (official end of the season), it receives information about the successful harvest and updated knowledge about the system, processes and updates the cropping system for the second season and forwards this updated cropping system to the operational model. At the end of the second season, the same process occurs, and soon after the second year begins.

7.4. APPLICATION CASE: THE NAMASTE SIMULATION MODEL

NAMASTE simulates farmers' adaptations to uncertain events such as climate change, water table depletion, the economic environment and agricultural reforms. We applied NAMASTE to a case study located in Karnataka state, India, in the Berambadi watershed. The cropping system is organized around three seasons: i) the rainy season (kharif), when most crops are grown; ii) the winter season (rabi), when mainly irrigated crops are grown and iii) the dry season, when little cultivation occurs (summer). Monsoon rainfall is a key determinant of crop choice. Farmers make three types of decisions: i) whether to invest in an irrigation system, ii) crop selection and iii) crop management and operations. All farmers in the watershed pump irrigation water from the same aquifer, and those from the same village share labor and equipment.

To illustrate NAMASTE's ability to simulate farmers' adaptive decision-making processes under conditions of both limited and shared resources, we ran a baseline scenario over a 10-year planning horizon in which the parameters that describe the climate, crop market conditions (prices and costs), and water pumping conditions (i.e. hours of electricity available each day, cost of pumping) were based on those obtained from farmer surveys.

7.4.1. Coupling the farming system model to the hydrological model

Rainfall, market prices, and availability of electricity, labor, equipment, and irrigation water are inputs to the farming system. They are modeled as subsystems of an external system that limits the farming system (Figure 7.5).

Hydrological sub-system

AMBHAS (Tomer 2012) is a spatially explicit groundwater model that simulates dynamics of daily groundwater level based on equations from McDonald & Harbaugh (1988). It predicts daily groundwater level, actual net recharge and discharge. Net recharge is predicted from the amount of water drained below the soil profile and required for crop irrigation predicted by STICS for a 1 ha cell. The PYTHON code in AMBHAS was wrapped into an atomic model using difference equations in RECORD.

Climate, market and power supply sub-systems

The WEATHER model simulates expected and actual rainfall each day. The MARKET model simulates expected and actual crop market prices. The ELECTRICITY model simulates the number of hours of electricity available each day. These sub-models are implemented in an atomic model using difference equations in RECORD.

7.4.2. NAMASTE simulaton

When resources are shared, interactions are important to an individual farmer's decision-making process. To integrate resource constraints into the farming system model, our experimental model simulates a virtual village composed of two virtual farms that have access to groundwater in the same AMBHAS cell of 3 ha (Figure 7.5). The first farmer manages 1 ha of land organized into two crop plots and owns one bullock for cropping operations; the second manages 2 ha of land organized into two crop plots and owns two bullocks. Neither farmer owns a tractor. On each farm, both the farmer and his wife work. Both farms can hire labor and rent equipment from the village (i.e. 110 female laborers, 90 male laborers, 4 bullocks, 1 tractor). Because a borewell can be drilled on each plot, this NAMASTE simulation consisted of four borewell models. During simulation, the strategic decision model may change the parameters for pump horsepower and well depth. The net recharge (water drained minus water pumped) returned to the AMBHAS cell is calculated by an intermediate model that calculates the difference between total drainage and pumping flows of all plots.

NAMASTE simulation of two farms in one village proceeds as follows. Each farm is simulated by a decision system, which includes strategic, tactical and operational decision models. NAMASTE considers farm characteristics (e.g. number of plots, soil type, amount of labor and equipment), crop management files and initial farm status as initial conditions. The operational decision model manages the village's labor and equipment that is used for crop production. It functions as a resource manager and attributes resources to the first enquirer. The operational model interacts with the operating system, while the biophysical system has as many STICS models as there are plots in the village. The external system (i.e. WEATHER, MARKET and ELECTRICITY models) constrains both farms in the same way, and we assume that farmers' individual or combined decisions do not influence it. The same AMBHAS cell simulates the irrigation water available to both farms.

At the beginning of the year, in the strategic model, each farmer makes decisions about investment and the cropping system for the next ten years independent of other farm decisions. Investment in a borewell determines parameters of the borewell model for each plot. At the beginning of the cropping season, in the tactical model, each farmer independently updates the cropping system based on new information on prices, rainfall and groundwater level. This updated cropping system is then entered into the operational model, which defines the crop rotation and the management of each crop. The operational model determines when conditions necessary for crop operations are met and requests resources from its resource manager. Farmers' practices interact at this level, which means that one farmer's crop operations may be restricted by the other's when both need labor and equipment at the same time. Irrigation water may also be a source of conflict between farmers, since the water that one farmer withdraws from the aquifer is no longer available to the other (Figure 7.5).

7.4.3. Calibration and validation

The model was calibrated with data from two farm surveys conducted in the Berambadi watershed. Farmers on the watershed were surveyed in 2014 and 2015. The first survey targeted 27 farmers to obtain detailed data about their practices, especially their decisions and how they adapted them. The second survey targeted 684 farmers to obtain broad data on farm characteristics and the social, economic and agronomic environments. This survey enabled creation of a typology of farmers on the watershed based on biophysical factors (e.g. farm location, soil type, groundwater accessibility), economic factors (e.g. farm size, labor, equipment) and social factors (e.g. castes, family structure, education, off-farm job) (for more details, see Robert et al. (submitted)). We surveyed seed retailers and village leaders (panchayats) to learn about recommended crop management practices and village organization. Additionally, 52 experimental plots were monitored over three years, which provided empirical data on crop production and management. These data helped supplement the verbal information that farmers provided during surveys. Meteorological data were obtained from a meteorological station and water gauges installed on the watershed. Prices and costs were obtained from farmers and official district data from the Indian Ministry of Agriculture and Cooperation (Directorate of Economics and Statistics) and the National Informatics Center (Agricultural Census Division).

The model was validated using computerized model verification and operational validation. Computerized model verification checks whether the computer implementation corresponds to the conceptual model representation (Whitner and Balci 1986; Sargent 2013). It verifies that the computer code has no coding errors or computer bugs and that the simulation language is implemented well. We used two main approaches for computerized model verification: i) static, which tests the main script at multiple points, allowing for local checks during encoding, and ii) dynamic, which executes the script with several sets of data and experimental conditions to verify the accuracy of outputs. In contrast, operational validation checks whether the behavior of the final simulation model is accurate enough to fulfill the research objectives. The model was validated mainly by subjectively exploring its behavior (Sargent 2013). First, we graphically compared model predictions to observed data, verifying that predicted yields lay within the ranges of observed yields in the watershed. We also qualitatively analyzed model behavior, verifying that predicted variables moved in the same directions as observed variables. For example, we verified that crop choice, management and yield correctly responded to climate variations; that investment in irrigation corresponded to economic and climate environments; and that the groundwater table correctly responded to rainfall and irrigation.

7.4.4. Simulation results

Sequential decision making and adaptation at different temporal and spatial scales

To illustrate decision processes and adaptations, we describe the sequential decision-making processes the first farmer followed to cultivate 1 ha of land (Figure 7.6). At the beginning of the 10-year planning horizon, the farmer has expectations for the future climate (i.e. percentage chances that a year will have good, above-average, average, below-average or poor rainfall). Farmers' expectations for the climate influence those for socio-economic and hydrological conditions (crop prices and groundwater level, respectively). Based on these expectations, the farmer plans long-term investment (e.g. adding a borewell) associated with an optimal cropping system choice (first column, Figure 7.6). At the tactical level, the farmer knows what kind of climate to expect (i.e. average rainfall) but is uncertain about the seasonal distribution of rainfall throughout the year. The farmer observes the groundwater level (*H*) at the beginning of each year (initially 60 m.b.g.l.; simulated observations in later years come from the operational decision model) and has expectations for how it will change throughout the year (i.e. *expected H*). The farmer reviews the cropping system decision (second column, Figure 7.6) and begins daily crop operations (operational decisions) (third column, Figure 7.6).

The farmer can adapt crops and/or practices when conditions are not suitable. In the fourth year, which had below-average rainfall, the farmer adapted crop choice at the tactical level. The farmer, knowing that low rainfall during the cropping season impacts rainfed crops in particular and observing a groundwater level much higher (12.4 m higher) than expected at the beginning of the planning horizon, changed 0.1 ha of rainfed marigold to irrigated sunflower (to go with the 0.9 ha of irrigated tumeric).

In the third year, which had above-average rainfall, the farmer adapted crop choice at the operational level. The farmer planned to grow 0.9 ha of turmeric and 0.1 ha of marigold. Both crops have similar sowing windows (30 March−1 May) and conditions (rules): soil moisture must be low enough to bear loads (rule: < 75% of field capacity) but high enough for seeds to germinate (rule: > 60% of field capacity) and rain must not be forecast for two consecutive days (since sowing can last two days) (rule: total expected rainfall for two consecutive days must not exceed 5 mm). Five days in April (6, 7, 8, 9 and 11) had acceptable soil moisture (60-75% of field capacity), but April's high rainfall (147 mm) prevented sowing. Because sowing turmeric and marigold was not possible, the farmer had to review the cropping plan and sow only maize, which has a wider sowing window (April -June).

In the sixth year, which had above-average rainfall, the farmer adapted practices at the operational level. Unlike in the third year, turmeric and sunflower could be sown in April; however, frequent rainfall events after sowing decreased the number of irrigation events planned for turmeric. Four planned irrigation events were cancelled because irrigation rules recommend irrigating when total rainfall during the past three days is < 50 mm and < 5 mm of rainfall is expected in the next two days.

Tactical and operational adaptations influenced the groundwater level and the farmer's profit (Figure 7.7). Due to generally adequate rainfall during the planning horizon (except the 4^{th}, 9^{th} and 10^{th} years), pumping was lower and recharge was higher than predicted at the strategic level. Thus, the groundwater level did not decrease as much as expected, and the borewell did not go dry during the planning horizon. Concerning profit, rainfall induced economically disastrous years (i.e. 3^{rd} and 9^{th} years), by preventing the farmer's initial cropping system plan and requiring maize to be sown, or highly profitable years (i.e. the 6^{th} year), by being above average and well distributed during crop growth. In at least one year (i.e. the 10^{th}) irrigation was able to compensate for the below-average rainfall and provide a profit.

Resource management: between scarcity and sharing

NAMASTE considers situations in which resources may be limited because they are scarce and limited and/or used by another farmer. In these conditions, farmers adapt their daily practices, delaying crop operations until resources become available. Competition for resources can be internal, when operations occur at the same time in two plots of the same farm, or external, when competition due to another farmer's practices.

To illustrate resource management in NAMASTE, we describe management of village resources (female and male labor, a tractor and bullocks) in the first year of the planning horizon (Figure 7.8). The first farmer planned to grow turmeric on 0.9 ha with 16 irrigation events and rainfed marigold on 0.1 ha. The second farmer planned to grow turmeric on 1.6 ha with 12 irrigation events and rainfed marigold on 0.4 ha. Three types of resource conflicts were observed (Figure 7.8):

i) Conflicts over use of the tractor to plow land. Turmeric and marigold plots must be plowed during the same window (1-23 March) and according to the same conditions (rules). Since turmeric has a higher priority index than marigold, the resource manager allocates the tractor to the turmeric plots first (e.g. the first tractor plowing occurs on 10-11 March for turmeric plots and 15-16 March for marigold plots). Between turmeric plots, the resource is randomly attributed. For example, for turmeric, the first tractor plowing occurs on March 10th on farm 1 and March 11th on farm 2 and the second tractor plowing occurs on March 20th on farm 1 and on March 21st on farm 2.

ii) Conflicts over use of female labor to weed turmeric (10 April–5 September). Since both turmeric plots were sown on 13 April, they had the same time windows for weeding events (10-35, 55-65, 85-95 and 115-125 days after sowing). For each weeding event, the first farmer needed 21 male and 52 female laborers, and the second farmer needed 36 male and 91 female laborers. Since the village had only 110 female laborers, both farmers could not weed their plots at the same time. The resource is randomly attributed.

iii) Conflicts over use of both female and male labor to harvest turmeric. The first farmer needed 49 male and 58 female laborers, and the second farmer needed 87 male and 103 female laborers to harvest their turmeric plots. Since both female and male labor was limited, one of the farmers had to delay harvest.

7.5. DISCUSSION

Understanding farmers' decision-making processes and relationships with the biophysical system is necessary to understand farming system complexity at multiple scales. NAMASTE is 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. The model has two main innovations: i) its decision model simulates farmers' decision-making processes by describing dynamic sequential decisions via adaptation to the biophysical environment and ii) it couples decisional, economic, biophysical and hydrological systems to predict effects and spillover of human decisions on natural systems.

Research increasingly considers farm management as a flexible and dynamic process. In recent agricultural literature, however, consequences on long- and short-term farm organization are rarely considered, even though they appear to influence farmers' decision-making greatly (Daydé et al. 2014). We used the basic definition of Le Gal et al. (2011), which divides a decision into a set of interconnected decisions made over time and at multiple spatial scales. Sequential and dynamic representation is particularly useful and appropriate for modeling entire processes for making strategic, tactical and operational decisions (Risbey et al. 1999; Le Gal et al. 2011).

Like many agent-based models that represent a complete system (An 2012), coupling decisional, economic, biophysical and hydrological models was necessary to model and quantify spatio-temporal variability in water resources and interactions among groundwater, agricultural practices and crop growth. One difficulty in modeling these processes is combining independent models that were originally developed for specific purposes at different spatial and temporal scales (Kraucunas et al. 2015). The biophysical model used in NAMASTE was developed to simulate fixed practices such as sowing, irrigation and harvest on one plot for one cropping season. The hydrological model simulates groundwater dynamics of a large territory. The decision model describes farmers' decisions and practices on their farms. Meaningful model integration requires consistency in the underlying system boundaries, assumptions and scale of analysis of these diverse models in the global model. As Kling et al. (2016) suggested, it is necessary to develop "bridge" models that convert outputs of one model into inputs of another. This approach enables models to be connected at different scales and to operate together by downscaling outputs from global to local models (e.g. AMBHAS) and by upscaling outputs from local to global models (e.g. decision and biophysical models). This can ensure that component models are manageable and provide outputs at both local and global scales (Hibbard and Janetos 2013).

In this study, operational validation was performed mainly by subjectively and qualitatively exploring model behavior (Sargent 2013). We developed 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. Nonetheless, quantitative simulation results for the Berambadi case study still have high uncertainty. Calibrating and validating the global model is an important and time-consuming step that is still underway (94 parameters are directly accessible in the global model, and AMBHAS and STICS have many internal parameters that require tedious calibration).

Upscaling from the farm level to watershed, regional and national levels is a common approach for studying system behavior and dynamics, such as farm adaptations to climate change (Gibbons et al. 2010), land use and land cover changes in response to climate change (Rounsevell et al. 2014) and ecosystem changes in response to biotic and abiotic processes (Nash et al. 2014). Peters et al. (2007) identified three types of scales: "fine" (one individual), "intermediate" (groups of individuals) and "broad" (large spatial extents such as the landscape, region and planet). The appropriate scale is defined by the research question or hypothesis and often requires upscaling or downscaling existing models (Gibbons et al. 2010). We consider the upscaling issue from the perspective of modeling consequences of farmers' adaptations to changes in climate and groundwater. The challenge of aggregation or upscaling is to determine which fine-scale details matter most at intermediate or broad scales. Research questions differ according to the scale. At the farm scale, we focused on farmers' decision-making processes and their adaptation to uncertain changes (e.g. climate and resource availability). The watershed level requires exploring the influence of decision making on the groundwater table rather than the process of decision making itself and to consider interactions between individuals for shared resources. At the watershed level, relative trends are more important than absolute values. For example, at the watershed level we are more interested in the total amount of groundwater used for irrigation in the watershed than on individual farms.

Our model provides tools to analyze, evaluate, and optimize agronomic, environmental and economic criteria. We tested the model with a baseline scenario to simulate current farming practices in the Berambadi watershed and predict influence of the latter on groundwater level in a virtual village composed of two farms. Modeling agricultural production scenarios can help stakeholders make decisions about regulations and resource restrictions and encourage new practices to recommend to farmers.

7.6. CONCLUSION

We developed an original simulation model of a farming system that combines relevant principles highlighted in the scientific literature. The model was initially developed to address critical issues of groundwater depletion and farming practices in a watershed in southwestern India. Its structure, frameworks and formalisms can be applied to other agricultural contexts. Our application focused on water management in semi-arid agricultural systems, but the model can also be applied to other farming systems to confirm the reusability and robustness of the framework.

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FIGURE CAPTION

Figure 7.1. Representation of farmers' decision-making processes at multiple temporal and spatial scales, indicating processes to adjust farm management to the farm environment.

Figure 7.2. Conceptual representation of the farming system based on integration of three systems. Based on knowledge, farmers make decisions that the operating system translates into executable actions. These actions modify the state of the biophysical system. Specific outputs for irrigation management provide information about water consumption and natural drainage of groundwater.

Figure 7.3. A) Activity plan of the sequence of sorghum operations created with the decision extension. B) Rules and associated predicates for the activity plan of the sequence of sorghum operations.

Figure 7.4. Sequence diagram of the event flow in systemic modeling of the farming system. We considered two cropping seasons (days 100-250 and 251-355) and two operations (sowing order on day 130 and harvest order on day 240. O.S. = operating system, LT = long-term

Figure 7.5. NAMASTE model: a virtual village composed of two virtual farms (F1 and F2), each having access to ground water on the same AMBHAS cell. Each farm is simulated by two individual DEVS atomic decision model (strategic and tactic) and a common operational decision model using the VLE decision extension of RECORD that describes individual operational decisions for the whole village. The WEATHER model, the MARKET model and the ELECTRICITY model constrain the same way both farms. Farm 1 contains two plots P1 and P2, Farm 2 contains two plots P1 and P2. GW = groundwater, HP = horsepower

Figure 7.6. Decisions and adaptations of one farmer during the 10-year planning horizon (each line describes one year). The first column describes the farmer's strategic decisions about investment in irrigation. The second column describes the farmer's tactical decisions and adaptations at the beginning of each year after observing the weather and the groundwater level. The third column describes the farmer's operational decisions about and adaptations to crop choice and irrigation after observing daily rainfall. Numbers in brackets indicate the number of irrigation events for each crop. CS = cropping system, π = profit, Rs = Indian rupees, H = groundwater level, m.b.g.l. = meters below ground level.

Figure 7.7. Groundwater level and profit of one farmer during the 10-year planning horizon – comparison of expected values at the strategic level (optimal profit and expected groundwater level from strategic decisions) and final values at the operational level. H = groundwater level, m.b.g.l. = meters below ground level, Rs = Indian rupees (bleu drops describe rainfall types: 1 drop is poor rainfall, 2 drops is below-average rainfall, 3 drops is average rainfall, 4 drops is above-average rainfall, 5 drops is good rainfall).

Figure 7.8. Resource management in a village composed of two farms – example of available (in %) village resources (female and male labor, bullocks and tractor) during the first year of the planning horizon. Three conflicts are identified (1, 2, 3). Activities of one farm were postponed when resource conflicts occurred.

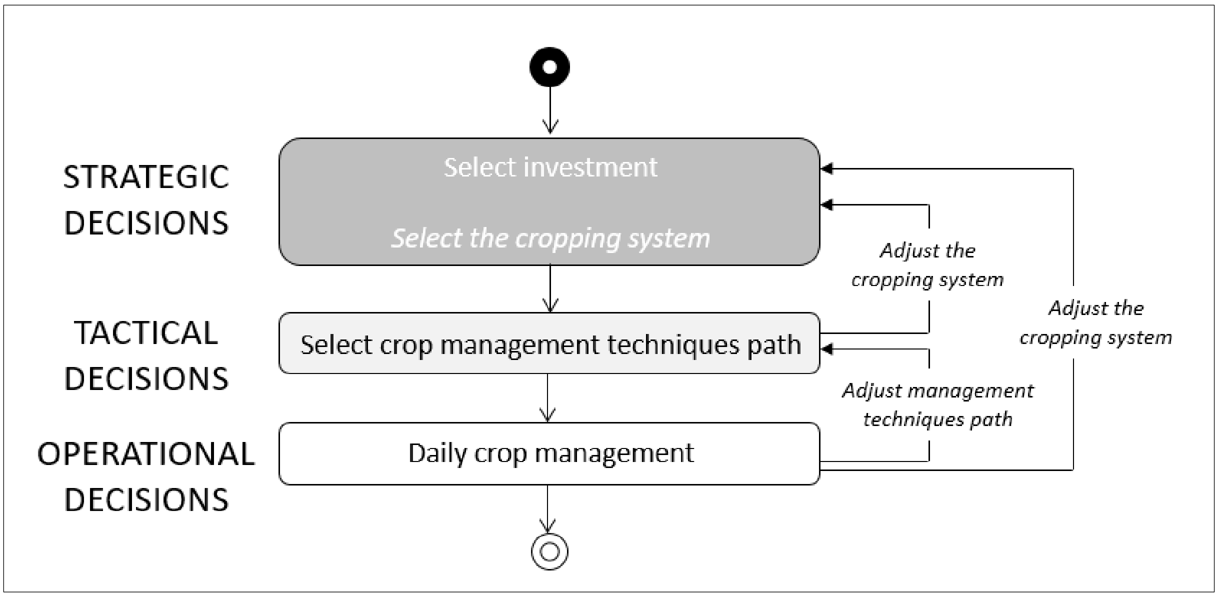


Figure 7.1

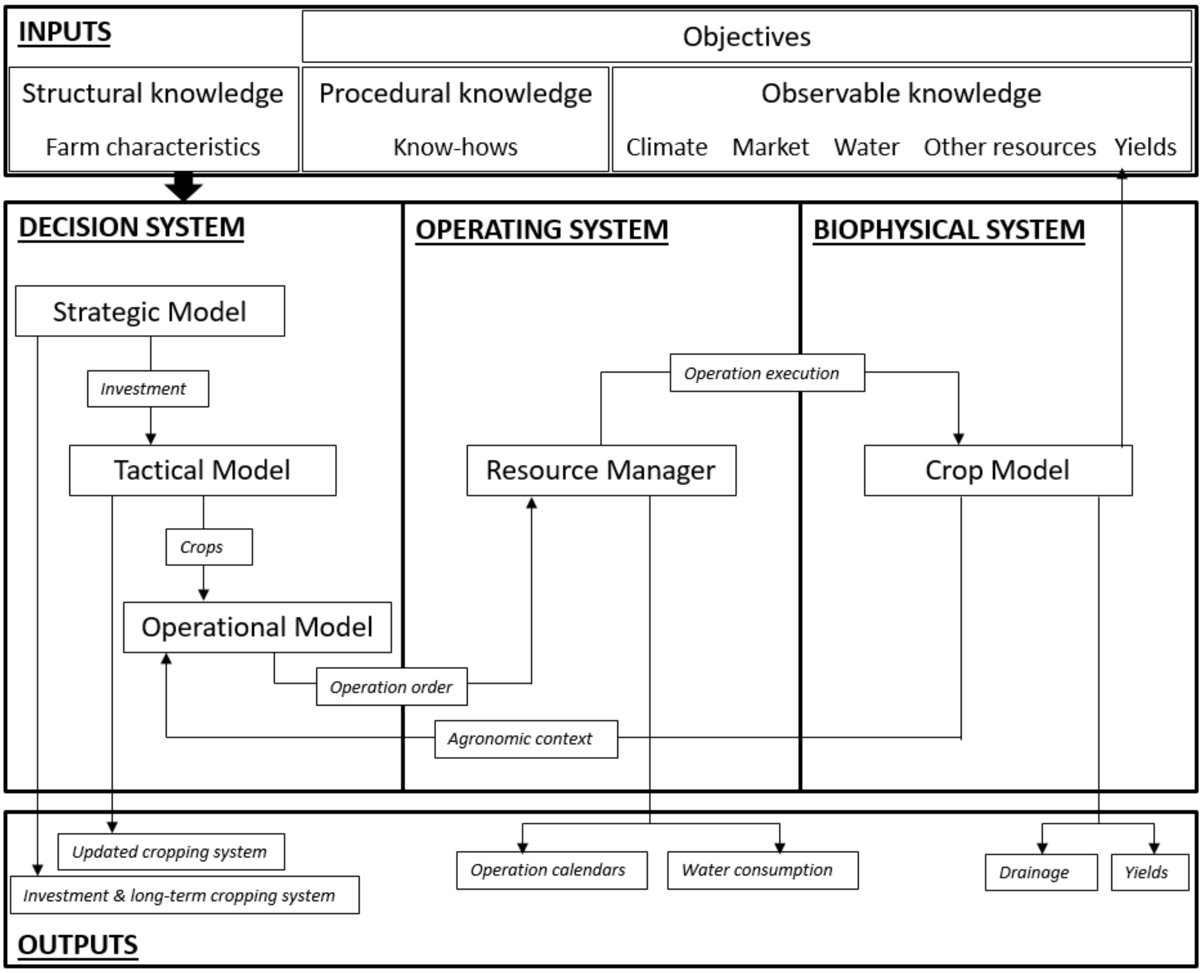
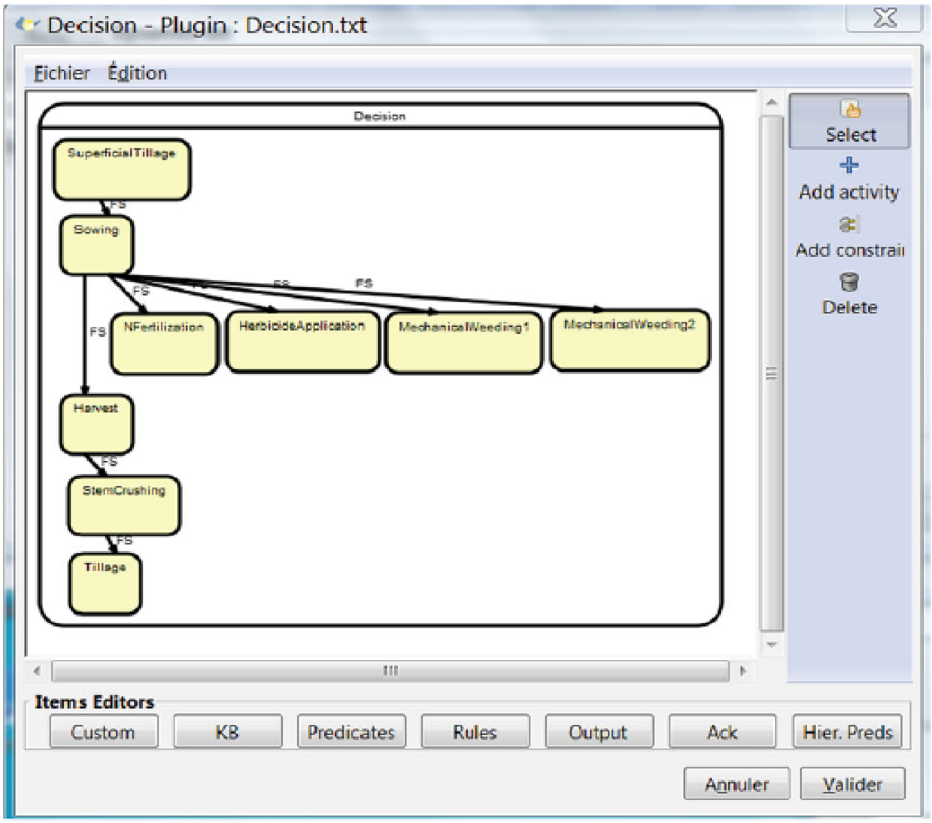


Figure 7.2

A)


Decision - Plugin : Decision.txt
Fichier
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Sowing
FS
NFertilization
HerbicideApplication
MechanicalWeeding1
MechanicalWeeding2
Harvest
StemCrushing
Tillage
Select
Add activity
Add constrai
Delete
Items Editors
Custom
KB
Predicates
Rules
Output
Ack
Hier. Preds
Annuler
Valider

B)

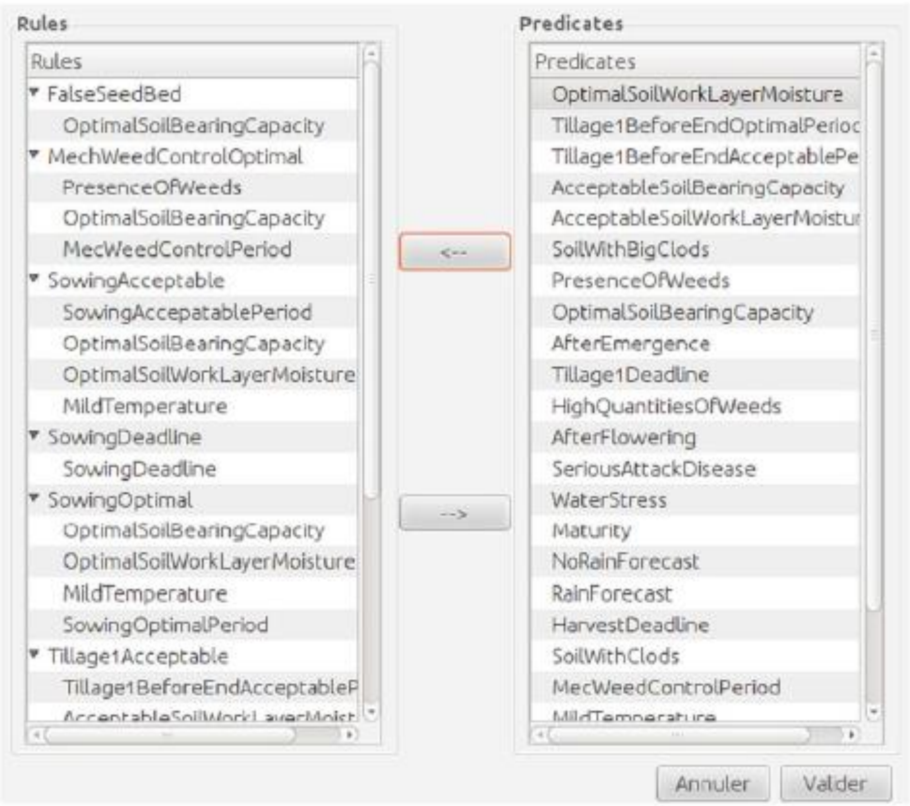

Rules
Rules
FalseSeedBed
OptimalSoilBearingCapacity
MechWeedControlOptimal
PresenceOfWeeds
OptimalSoilBearingCapacity
MecWeedControlPeriod
SowingAcceptable
SowingAccepatablePeriod
OptimalSoilBearingCapacity
OptimalSoilWorkLayerMoisture
MildTemperature
SowingDeadline
SowingDeadline
SowingOptimal
OptimalSoilBearingCapacity
OptimalSoilWorkLayerMoisture
MildTemperature
SowingOptimalPeriod
Tillage1Acceptable
Tillage1BeforeEndAcceptableP
<--
-->
Predicates
Predicates
OptimalSoilWorkLayerMoisture
Tillage1BeforeEndOptimalPerioc
Tillage1BeforeEndAcceptablePe
AcceptableSoilBearingCapacity
AcceptableSoilWorkLayerMoistu
SoilWithBigClods
PresenceOfWeeds
OptimalSoilBearingCapacity
AfterEmergence
Tillage1Deadline
HighQuantitiesOfWeeds
AfterFlowering
SeriousAttackDisease
WaterStress
Maturity
NoRainForecast
RainForecast
HarvestDeadline
SoilWithClods
MecWeedControlPeriod
Annuler
Valider

Figure 7.3

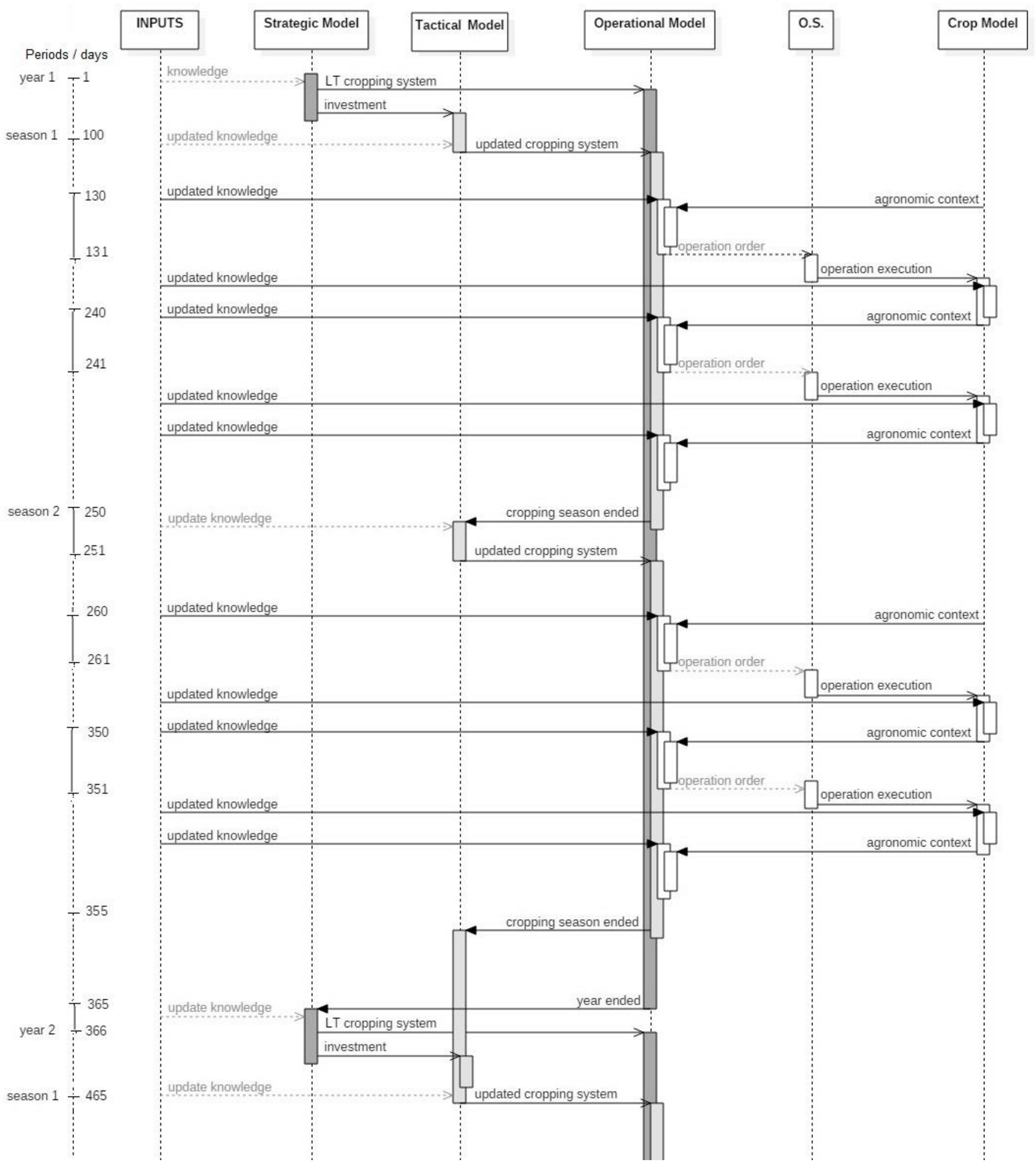

INPUTS
Strategic Model
Tactical Model
Operational Model
O.S.
Crop Model
Periods / days
year 1
1
season 1
100
130
131
240
241
season 2
250
251
260
261
350
351
355
365
year 2
366
season 1
465
knowledge
LT cropping system
investment
updated knowledge
updated cropping system
agronomic context
operation order
operation execution
update knowledge
cropping season ended
year ended

Figure 7.4

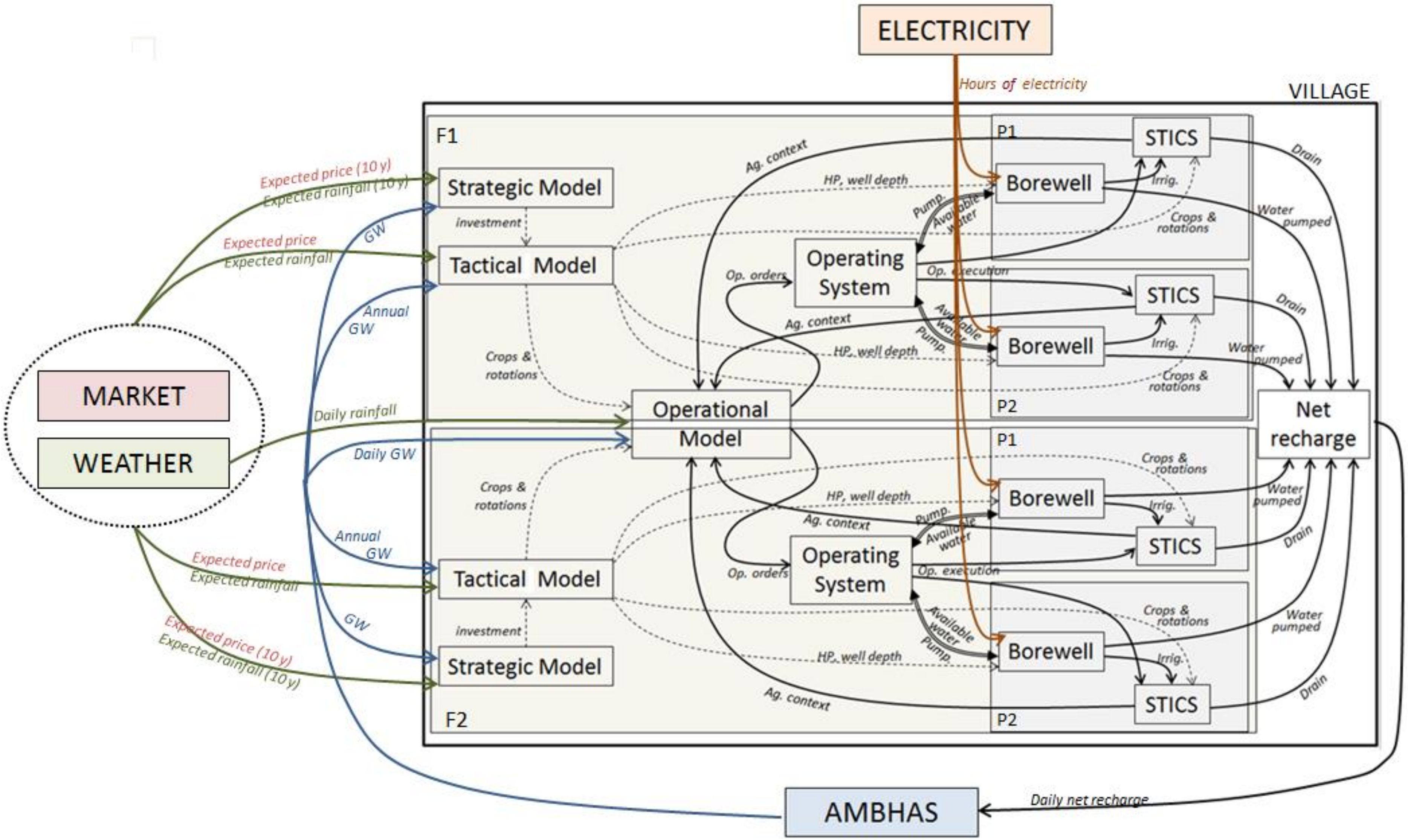
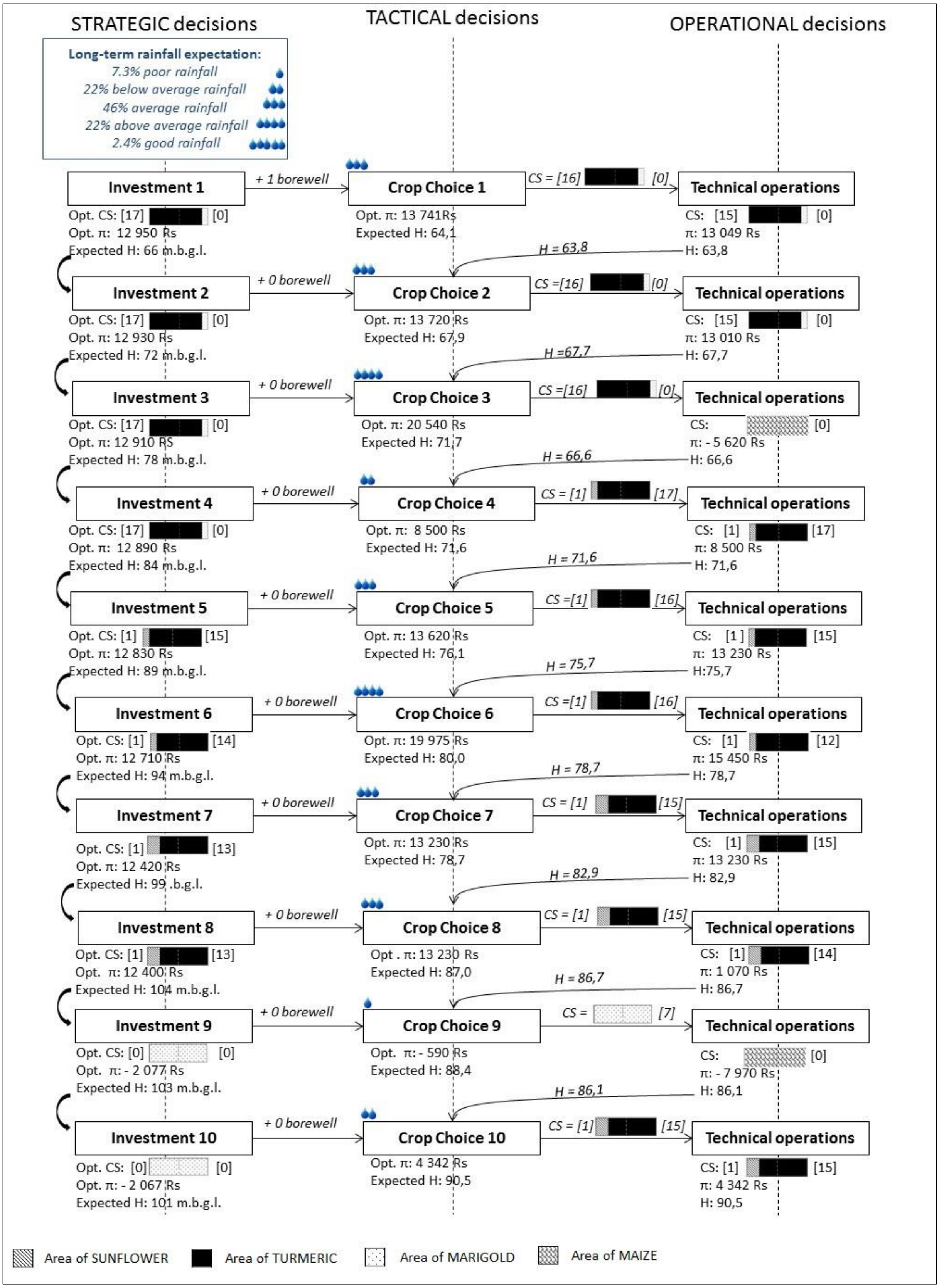

ELECTRICITY
Hours of electricity
VILLAGE
F1
P1
STICS
Borewell
Strategic Model
Tactical Model
Operating System
Operational Model
P2
Net recharge
MARKET
WEATHER
F2
AMBHAS
Daily net recharge
Expected price (10 y)
Expected rainfall (10 y)
Expected price
Expected rainfall
GW
Annual GW
Daily rainfall
Daily GW
investment
Crops & rotations
Ag. context
HP, well depth
Pump.
Available water
Op. orders
Op. execution
Irrig.
Drain
Water pumped

Figure 7.5



STRATEGIC decisions
TACTICAL decisions
OPERATIONAL decisions
Long-term rainfall expectation:
7.3% poor rainfall
22% below average rainfall
46% average rainfall
22% above average rainfall
2.4% good rainfall
Investment 1
+ 1 borewell
Crop Choice 1
CS = [16] [0]
Technical operations
Opt. CS: [17] [0]
Opt. π: 12 950 Rs
Expected H: 66 m.b.g.l.
Opt. π: 13 741Rs
Expected H: 64,1
CS: [15] [0]
π: 13 049 Rs
H: 63,8
H = 63,8
Investment 2
+ 0 borewell
Crop Choice 2
CS =[16] [0]
Technical operations
Opt. CS: [17] [0]
Opt. π: 12 930 Rs
Expected H: 72 m.b.g.l.
Opt. π: 13 720 Rs
Expected H: 67,9
CS: [15] [0]
π: 13 010 Rs
H: 67,7
H =67,7
Investment 3
+ 0 borewell
Crop Choice 3
CS =[16] [0]
Technical operations
Opt. CS: [17] [0]
Opt. π: 12 910 RS
Expected H: 78 m.b.g.l.
Opt. π: 20 540 Rs
Expected H: 71,7
CS: [0]
π: - 5 620 Rs
H: 66,6
H = 66,6
Investment 4
+ 0 borewell
Crop Choice 4
CS = [1] [17]
Technical operations
Opt. CS: [17] [0]
Opt. π: 12 890 Rs
Expected H: 84 m.b.g.l.
Opt. π: 8 500 Rs
Expected H: 71,6
CS: [1] [17]
π: 8 500 Rs
H: 71,6
H = 71,6
Investment 5
+ 0 borewell
Crop Choice 5
CS =[1] [16]
Technical operations
Opt. CS: [1] [15]
Opt. π: 12 830 Rs
Expected H: 89 m.b.g.l.
Opt. π: 13 620 Rs
Expected H: 76,1
CS: [1] [15]
π: 13 230 Rs
H:75,7
H = 75,7
Investment 6
+ 0 borewell
Crop Choice 6
CS =[1] [16]
Technical operations
Opt. CS: [1] [14]
Opt. π: 12 710 Rs
Expected H: 94 m.b.g.l.
Opt. π: 19 975 Rs
Expected H: 80,0
CS: [1] [12]
π: 15 450 Rs
H: 78,7
H = 78,7
Investment 7
+ 0 borewell
Crop Choice 7
CS = [1] [15]
Technical operations
Opt. CS: [1] [13]
Opt. π: 12 420 Rs
Expected H: 99 .b.g.l.
Opt. π: 13 230 Rs
Expected H: 78,7
CS: [1] [15]
π: 13 230 Rs
H: 82,9
H = 82,9
Investment 8
+ 0 borewell
Crop Choice 8
CS = [1] [15]
Technical operations
Opt. CS: [1] [13]
Opt. π: 12 400 Rs
Expected H: 104 m.b.g.l.
Opt . π: 13 230 Rs
Expected H: 87,0
CS: [1] [14]
π: 1 070 Rs
H: 86,7
H = 86,7
Investment 9
+ 0 borewell
Crop Choice 9
CS = [7]
Technical operations
Opt. CS: [0] [0]
Opt. π: - 2 077 Rs
Expected H: 103 m.b.g.l.
Opt. π: - 590 Rs
Expected H: 88,4
CS: [0]
π: - 7 970 Rs
H: 86,1
H = 86,1
Investment 10
+ 0 borewell
Crop Choice 10
CS = [1] [15]
Technical operations
Opt. CS: [0] [0]
Opt. π: - 2 067 Rs
Expected H: 101 m.b.g.l.
Opt. π: 4 342 Rs
Expected H: 90,5
CS: [1] [15]
π: 4 342 Rs
H: 90,5
Area of SUNFLOWER
Area of TURMERIC
Area of MARIGOLD
Area of MAIZE

Figure 7.6

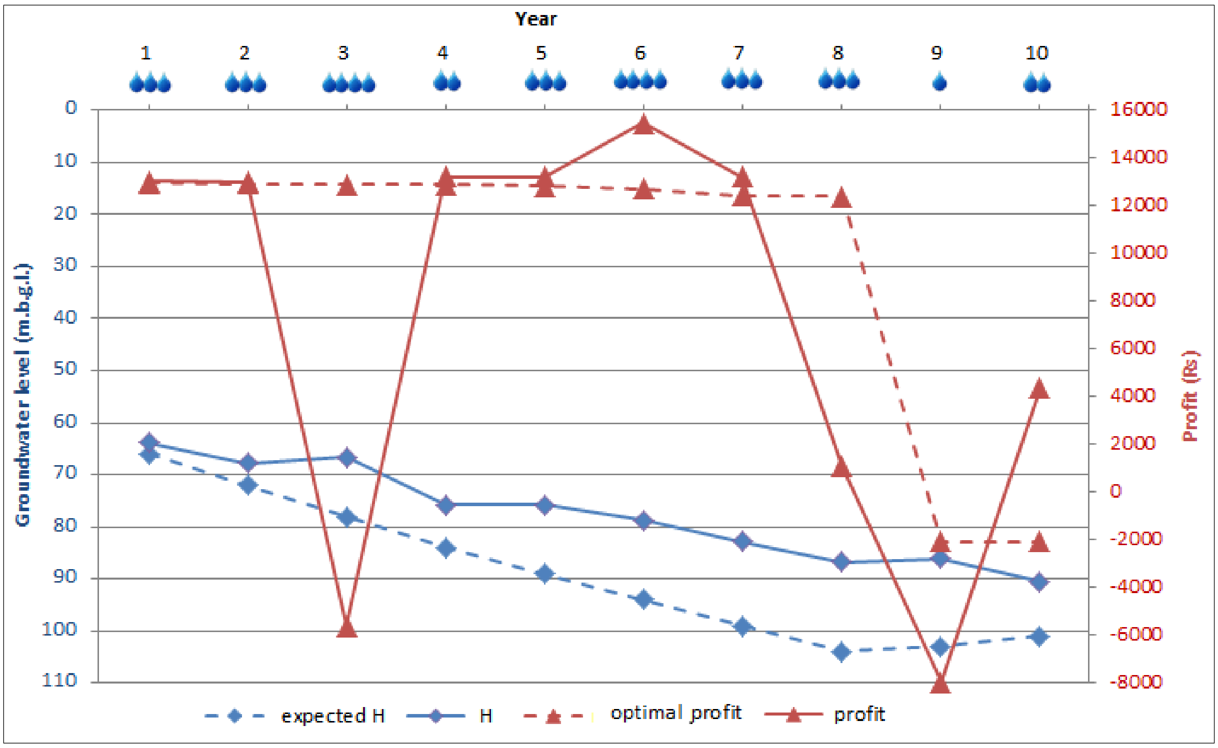
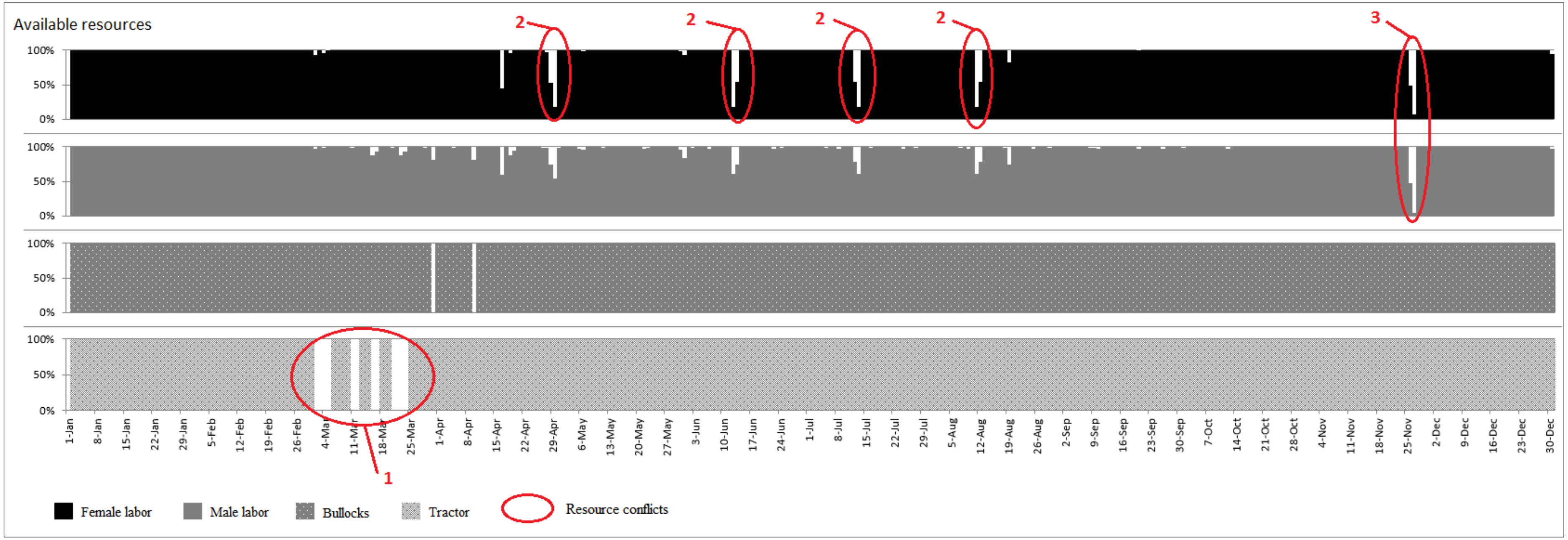

Year
1
2
3
4
5
6
7
8
9
10
Groundwater level (m.b.g.l.)
0
10
20
30
40
50
60
70
80
90
100
110
Profit (Rs)
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
expected H
H
optimal profit
profit

Figure 7.7



Available resources
100%
50%
0%
2
2
2
2
3
1
1-Jan
8-Jan
15-Jan
22-Jan
29-Jan
5-Feb
12-Feb
19-Feb
26-Feb
4-Mar
11-Mar
18-Mar
25-Mar
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
26-Aug
2-Sep
9-Sep
16-Sep
23-Sep
30-Sep
7-Oct
14-Oct
21-Oct
28-Oct
4-Nov
11-Nov
18-Nov
25-Nov
2-Dec
9-Dec
16-Dec
23-Dec
30-Dec
Female labor
Male labor
Bullocks
Tractor
Resource conflicts

Figure 7.8

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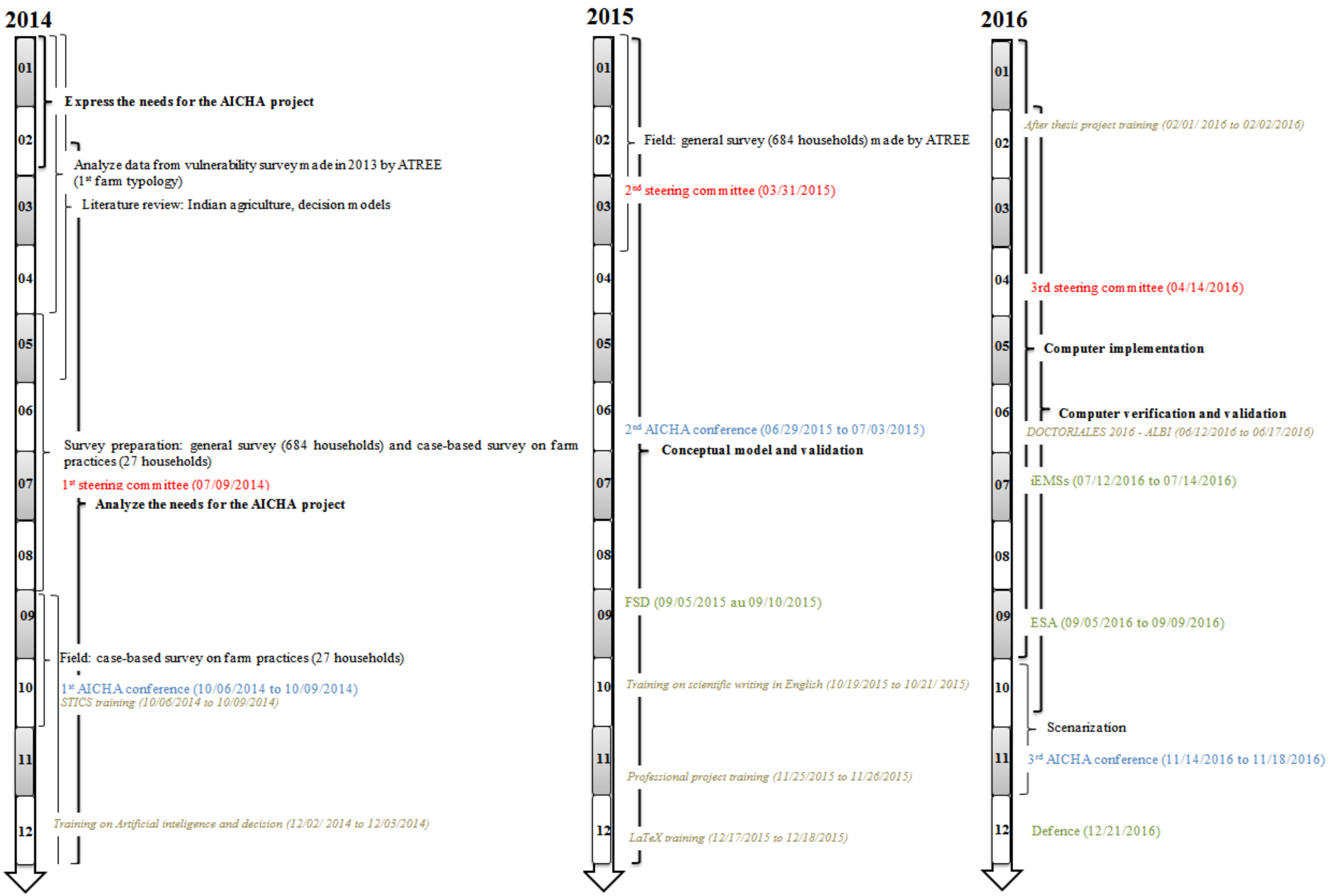
Appendix

APPENDIX 1: THESIS SEQUENCE OF EVENTS



APPENDIX 2: DATA USED IN NAMASTE DEVELOPMENT

Knowledge acquisition helps to understand and describe the real system.

1) We surveyed farmers in the watershed in 2014 and 2015.
2) We surveyed seed retailers and Panchayats (village leaders)
3) 52 experimental plots
4) Meteorological data
5) Crop prices and costs

1. Farm surveys

The first survey targeted 27 farmers to obtain detailed data about their practices, in particular their decisions and the process of adapting their decisions. The second survey targeted 680 farmers and obtained broad data about farm characteristics and social, economic and agronomic environment. This survey led to a typology of farmers on the watershed based on biophysical factors (e.g. farm location, soil type, ground water accessibility), on economic factors (e.g. farm size, labor, equipment), on social factors (e.g. castes, family structure, education, off-farm job) (details are found in Robert et al. (in Prep.)).

Questionnaire and survey work has been done under Dr Srinivas Badiger and Iswar Patil supervision (Ashoka Trust for Research in Ecology and the Environment, ATREE). A first draft of the questionnaire has been proposed prior to my arrival and then adapted to the Indian context and tested in the field with the ATREE team. In parallel, the "Big" survey targeting 600 households on the Berambadi watershed has been reviewed to fit the main expectations of the different INRA teams (EMMAH, AGIR, LERNA) and simplified to be applicable to the field.

1.1. The Case-based survey in the Berambadi watershed

The case-based survey aimed at getting detailed information concerning decision-making and rules that direct the decision process of the farmers in the Berambadi watershed.

1.1.1.Questionnaire design

We aimed at identifying the farmers' **objectives**, their **strategic cropping system** plan, and to understand how they **perceive their resources** (land, labor, irrigation water, material). We also wondered which indicators of change in the environment farmers are looking at, and how and when they are **monitoring** these changes (prices, weather, GW level). We supposed that farmers have **leeways** to adapt and face these changes such as obtaining temporary labor, using several sources of water, borrowing material, etc. We believed that farmers make decisions during the growing season in order to face and deal with the changing environment, and we wondered when these decisions are made, and how they are taken to identify **decision-rules**.

➢ <u>Initial questionnaire</u>

The questionnaire was composed of six main parts (Figure Appendix 2.1) – i) the objectives of the farmer, ii) his strategic plan and cropping pattern characteristics, iii) his crop management practices and decision rules, iv) his resources, v) his marketing system, and vi) his climate change consideration. A temporal graph (Figure Appendix 2.2) and stickers with decisions taken and crop operations was proposed to support the crop management part of the questionnaire.

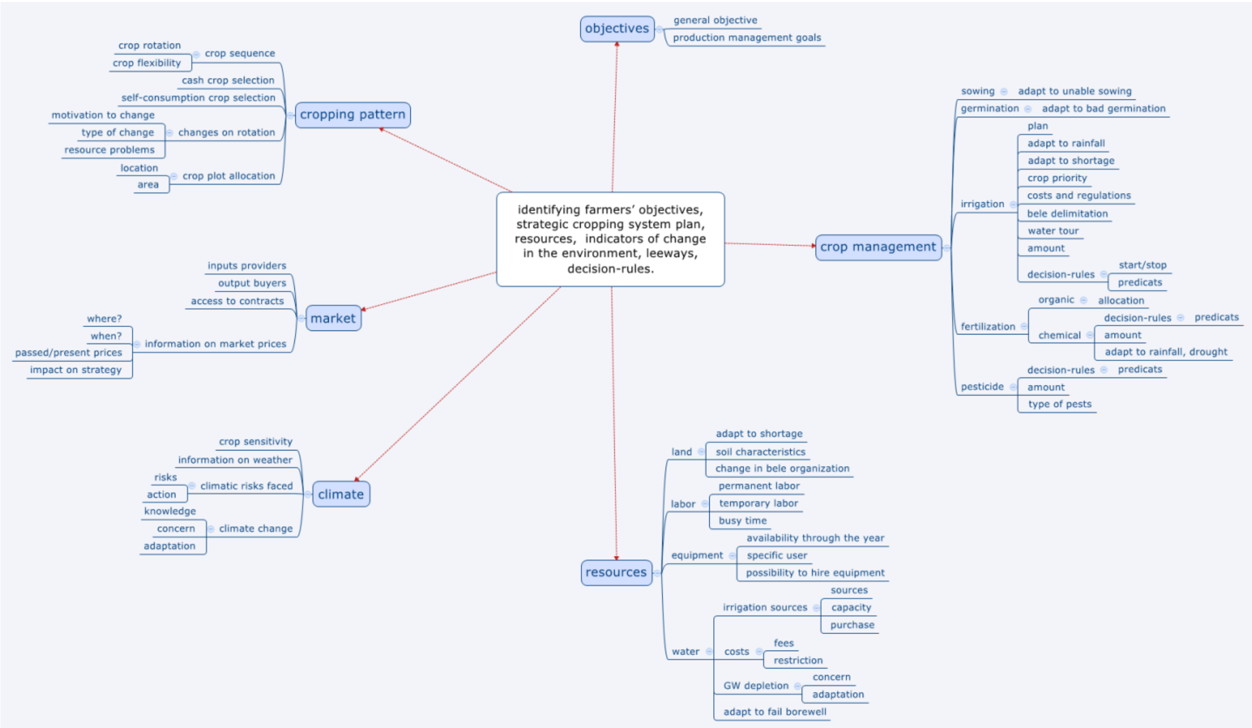


Figure Appendix 2. 1 Case-Based Survey Brainstorming

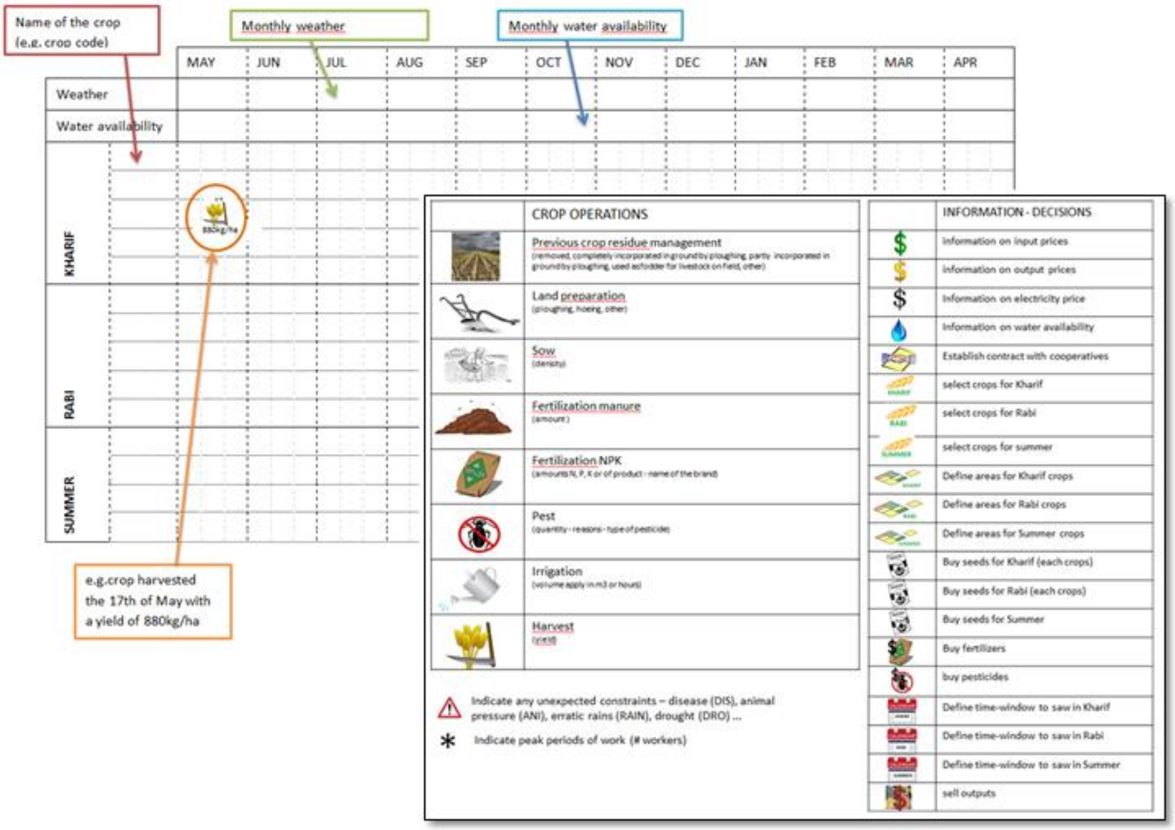


Figure Appendix 2. 2 Temporal Graph

➢ <u>Adaptation to the Berambadi case</u>

A six-hour preliminary test of the questionnaire had been done after reviewing the vocabulary and the meaning of each question with the ATREE team, concluding that the survey was way to long and numerous questions needed to be reviewed.

First, it appeared that farmers had difficulties answering open questions and needed numerous explanations and examples to answer. We decided to limit the number of open questions (79% in the first questionnaire draft, and 15% in the final questionnaire), and proposed instead multiple choices. To avoid situation where the farmer will agree with all the choices, we asked the farmer to rank his answers from the more likely to the less likely.

Then, it has been advised to avoid conflicting questions on costs and water/electricity fees to not antagonize some farmers.

Examples were preferred to agronomic vocabulary. Crop sequence, crop rotation, crop precedent effects are examples of agronomical concepts that farmers had difficulties to understand.

The use of the temporal graph was not encouraged fearing that some illiterate farmers got lost or ashamed during this exercise.

Finally, during the training of the enumerators, each question had been rewritten in a simple way to facilitate the understanding of the enumerators.

At the end, the questionnaire had been shortening to one and half hour to optimize the attention of the farmer.

1.1.2.Sample selection

The initial questionnaire was built with the idea that it will follow the « big » survey, so that general questions on household characteristics, and farm structure would not need to be asked again. Given that the « big » survey was started in the same time than the case-based survey, we decided to focus on farms with experimental plots followed by IISc. A demographic survey was done in June 2013 to gather general household information, farm structure and general crop management practices on the other beles of the farm.

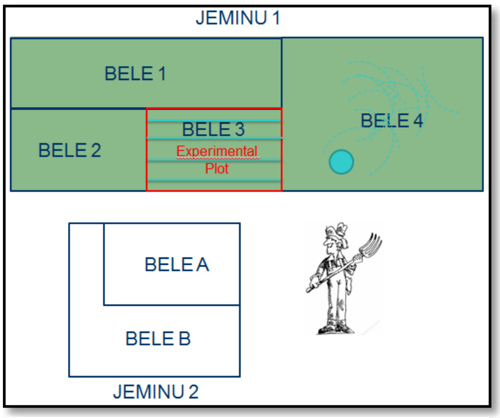


Figure Appendix 2. 3 Definition - Jeminu, Bele

We selected 27 farmers over the 52 followed by IISc (Figure Appendix 2.4). The sampling of cases was driven by a search for diversity rather than the search for representativeness. We selected candidates over 5 axes of diversification: ground water (GW) level gradient, access to irrigation, farm size, heterogeneous soil type, and location on the watershed.

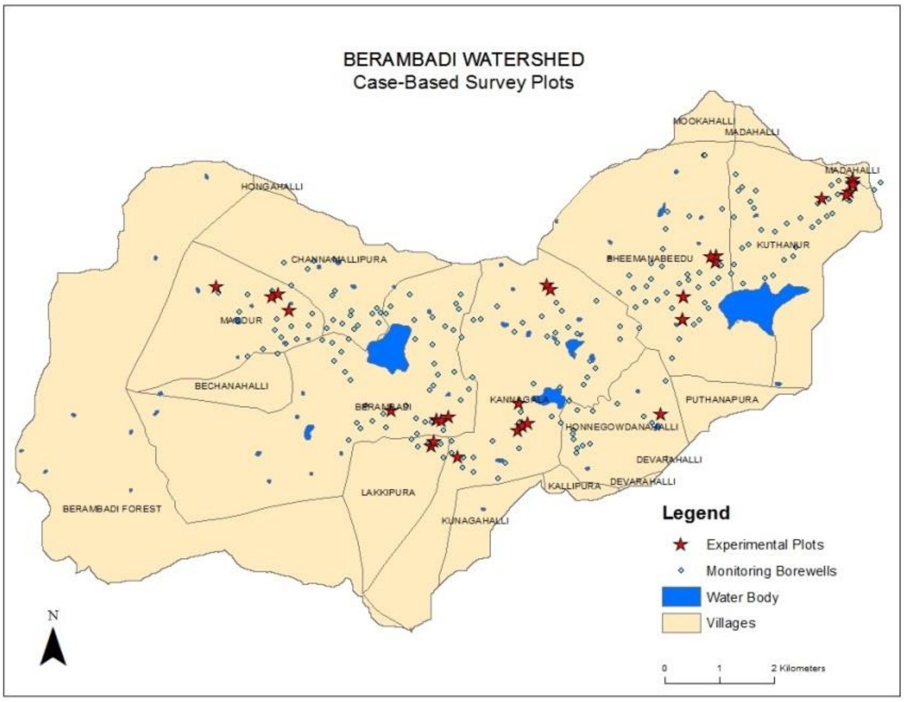


Figure Appendix 2. 4 Sample Farms Location

1.1.3.Interview process

Two enumerators who participated in the demographic survey in June 2013, surveyed the 27 farmers from the 24th of September to the 9th of October 2014. These persons were farmers' sons with a bachelor in education but limited knowledge in agronomy and farm practices in general.

Farmers were surveyed at their farm or their house depending on the time of the interview. One enumerator was asking questions in Kanada while the other was writing back the answers in English. In general, it was hard to keep the farmer concentrated for one and half hour, and some of them required to stop the interview and come back the day after so that they won't get delay too much in their daily farm tasks.

After a quick glance to the filled questionnaire, several issues had been lighted out: i) enumerators seemed to not understand the concepts of crop sequence, crop rotation and climate change in general, which bring the answers quite incoherent, ii) farms with temporary not working borewells for the past 3 years were considered as rainfed while most of them got water back in the borewell after the 2014 monsoon and so plan to irrigate in kharif 2015, iii) numerous questions where specifications were asked have not been filled up.

In order to check on the accuracy of certain information and complete some questions, we built a complementary questionnaire of 30 minutes specific to each farms. We targeted information on strategic/tactic decision-rules for crop choice, and crop allocation, and on operational decision-rules for sowing, fertilization, pest, and irrigation practices. We added questions on irrigation equipement investments and costs and type of labor contracts. We asked again questions on climate change and adaptations. Farmer also drawn their jeminus and beles, locates their irrigation sources, buildings, roads. This complementary study was led by Iswar who has the capacity and knowledge to engage a discussion with the farmer based on these questions. Farmers appeared to be more cooperative and interested in this type of exchanges. It also helped in checking decision sequences graphs issued from the first survey.

The aim of the project is to develop scenarios of water consumption by agriculture in changing climate. It is therefore necessary to understand farming practices that impact water use

Start the interview by describing the purpose of the survey: for academic research only, accurate answers are important and gratefully acknowledged, etc.

We are going to ask you some questions about your farm, the way you organise your production, the source of information you use, and about yourself and the family members involved in production. All is which will be treated confidentially.

1. Basic Information

Date	
Plot number	
Name of Village	
Panchayat Name	
Name of household head	
Caste	
Religion	
Farming Experience	

2. Household Information:

2.1. General information

Name	Relation with HH head*	Gender	Age in years	Education	Occupation**		Members fulltime work in own farm	Members temporarily work in own farm
					Primary	Secondary		

***** Head=**1**, Wife/Husband=**2**, Son/Daughter=**3**, Grandchild=**4**, Father/Mother=**5**, Sister/Brother=**6**, Niece/Nephew=**7**,Uncle/Aunt=**8**, Son/Daughter-In-Law=**9**,Father/Mother-In-Law=**10**, Brother/Sister-In-Law=**11**, Grandparent=**12,** others**=13**

****** Own agriculture work=**1**, Agriculture labour=**2**, Petty business=**3**, Dairy farming=**4**, Plantation worker=**5**, NTFP collecting=**6**, Livestock grazing=**7**, Factory worker=**8**, Pension earner (social security/Job pension)=**9**, Rural crafts (carpentry, blacksmith, pottery, weaving, goldsmith, basket making, leather work, etc.)=**10**, Government job=**11**, Commission agent=**12**, Contractor=**13**, Quarry worker=**14**, Bee keeper=**15,** Student=**16**, Domestic work (cleaning, cooking, water fetching, child care, fire making, washing clothes, etc) =**17**, Driver=**18**, Not working (Children/Aged/physical disable/illness etc.)=**19**, Mason= **20**, Other=**21** (specify)

2.2. Skill Training

Skill training received by HH member	Yes =1 No =0	Who?	Training received year	Name of the training Center	Subject matter of Training
Farm Related					
Dairy Related					
Livelihood Related					

2.3. Sources of Farm related Information

Sources of information	Information available
Agricultural Cooperative society	
Agricultural Extension service	
Agricultural school or University	
Farmer union	
Agricultural retailers	
Family and friends	
Press and media	
Farmers	
Krishi Mela	
Other specify	

3. General Farm characteristics

3.1. objective of farm

Objective of farming	YES	NO	Rank at least 4
Maintain income and livelihood stable			
Maintain farm in the family			
Minimize production cost			
Maintain crop diversity			
Maximize income			
Environmental friendly agriculture			

3.2. Specific Farm Characteristics:

a. Number of farms in different location and location identity	FARM 1	FARM 2
b. Farm Size (in acre)		
c. Farm ownership		
e. From how many years do you operate the farms		
g. Farm soil type		
h. Farm Buildings Type		
h.1. No of buildings		
h.2. Year of farm building constructed		
i. Farm distance from your home in Km		
j. Is farm has irrigation source?		
k. ownership of irrigation source(Own/Joint/Neighbor/Government)		
l. Irrigation method of each farm		
m. Do you have farm pond/Farm tank?		
n. Water Source for Pond/farm tank		
o. How many hours it take to fill?	-	

3.3. Manpower

Inform the number of labor needed in kharif 2014:

Activity wise Labour use	Number of Own Labour	Number of Hired Labour		Number of Permanent labour	No of Mutual Labour	Wage Paid(Average)	
		Male	Female			Male	female
Land Preparation							
Sowing							
Weeding							
Manure Application							
Fertilizer Application							
Harvest							
Threshing							

Inform the number of labor needed in rabi 2013:

Activity wise Labour use	Number of Own Labour	Number of Hired Labour	Number of Permanent labour	No of mutual labour	Wage Paid(Average) Male female
		Male	Female		
Land Preparation					
Sowing					
Weeding					
Manure Application					
Fertilizer Application					
Harvest					
Threshing					

3.4. Farm assets

Material type	Number of equipment	Owned=1 rent=2	Person using it
Tractor			
Tractor and implements			
Bullocks and implements			
Wooden plough			
Iron plough			
Seeder			
Weeder			
Pesticide sprayer			
Wheel barrow			
Treshing machine			
Organic manure pit			

3.5. Livestock Information:

Type*	Number	Present value	Reasons for keeping**
-	-	-	-

*Bulls=1, oxen=2, cow=3, buffalo=4, sheep=5, goat=6, poultry=8, pig=9

**own cultivation/Hiring out=1, manure=2, fuel (cooking) =3, milk=4, meat=5, egg=6

3.5.1.How do you manage manure from cattle?

- ☐ Use on land
- ☐ Give or sell to others
- ☐ Fuel (cooking)
- ☐ Others (be specific)

4. Decision rules

4.1. For the choice of your crops

4.1.1. How do you choose your crops?

(give 4 reasons and order)

- ☐ Crop choice is made according to water availability
- ☐ Crop choice depends on input costs
- ☐ The market for the crop is more accessible/crop easier to sell
- ☐ The price you expect is the leading factor
- ☐ You are familiar with growing these crops
- ☐ Crop choice depends on labour available (minimize working hours?)
- ☐ Suit to soil
- ☐ High yield
- ☐ Other (be specific

4.1.2. What are the crops usually grow for self-use purpose and cash purpose?

Need base crops	**Crop name**	**Percentage**
cash crops		
Self-consumption crops		

4.1.3. What is the usual crop sequence that you follow (e.g. Marigold – Maize – Marigold – Maize) in kharif? In rabi?

	Crop sequence (KHARIF)
RAINFED plots	
IRRIGATED plots	
	Crop sequence (RABI)
RAINFED plots	
IRRIGATED plots	

4.1.4. In general, what motivates you to change your crop sequence? (order if several)

- ☐ Change in market price
- ☐ Water availability low
- ☐ Weather (drought, erratic rainfall)
- ☐ Contract opportunities
- ☐ Neighbor’s action
- ☐ Pest and disease pressure
- ☐ Weed pressure
- ☐ Other (be specific)

4.1.5. If answer “change in market price” in 4.1.4. , which price are you referring to?

- ☐ Market price from last year
- ☐ Market price from last season
- ☐ Market price at the time of buying the seed

4.2. Cropping and Marketing information

4.1.1. Year 2014

4.2.1.1. When have you selected your crops for kharif 2014? (month, week)

4.2.1.2. When have you selected your crops for rabi 2014? (month, week)

4.2.1.3. When do you decide whether or not you will grow crops in summer?

4.2.1.4. When do you look for possible marigold contracts with companies (month, week)?

4.2.1.5. List the crops you grew in kharif, and plan to grow in rabi and summer this year:

Plot ID	5.5.1.Crop planted this season 2014 **KHARIF**	Acres	Irrigated (I) Rainfed (R)	.5.2. Crop to be planted this season 2014 **RABI**	Acres	Irrigated (I) Rainfed (R)	5.5.3. Crop to be planted this season 2015 **SUMMER**	Acres	Irrigated (I) Rainfed (R)

Year 2013

2013KHARIF

Plot ID	5.5.4. Crop planted in 2013	Irrigated (I) Rainfed (R)	acres	successful	failed	5.5.6. Quantity Harvested (Quintal)	5.5.7. Sold=1 Partly sold=2 Keep for own use=3	5.5.8. Price received/Quintal

2013 RABI

Plot ID	5.5.4. Crop planted in 2013	Irrigated (I) Rainfed (R)	acres	successful	failed	5.5.6. Quantity Harvested (Quintal)	5.5.7. Sold=1 Partly sold=2 Keep for own use=3	5.5.8. Price received/Quintal

Year 2012

2012 KHARIF

Plot ID	5.5.4. Crop planted in 2012	Irrigated (I) Rainfed (R)	acres	successful	failed

2012 RABI

Plot ID	5.5.4. Crop planted in 2012	Irrigated (I) Rainfed (R)	acres	successful	failed	5.5.6. Quantity Harvested (Quintal)	5.5.7. Sold=1 Partly sold=2 Keep for own use=3	5.5.8. Price received/Quintal

Year 2011

2011 KHARIF

Plot ID	5.5.4. Crop planted in 2011	Irrigated (I) Rainfed (R)	acres	successful	failed	5.5.6. Quantity Harvested (Quintal)	5.5.7. Sold=1 Partly sold=2 Keep for own use=3	5.5.8. Price received/Quintal

2011 RABI

Plot ID	5.5.4. Crop planted in 2012	Irrigated (I) Rainfed (R)	acres	successful	failed

4.2.2. Why do you grow watermelon in Kharif and cowpea in Rabi each year?

4.2.3. Why do you prefer to grow only one crop per season?

4.2. Farm Technical operations

4.3.1. Crop operation KHARIF 2014

For your crops grown in kharif 2014, inform:

	Crop1	Crop2	Crop3	Crop4
When did you do your land preparation? (month, week)				
When did you sow? (month, week)				
When did you buy your fertilizers? (month, week)				
When did you buy your pesticides? (month, week)				
When did you weed ? (month, week)				
When did you harvest ? (month, week)				
When will you sell your crops?				

4.3.2. Do you check the fertilizer and pesticide prices before buying it (be specific) or only when you buy it?

4.3.3. Do the pesticide and fertilizer prices influence your choice of crops?

4.3.4. Crop constraints Found in KHARIF 2014

Crop name	Type of constraint								
	Seed defect	Late sowing	Delayed rain	Heavy rain	Long dry spell	weed	Disease	Pests	Animal Pressure
a.									
b.									
c.									
d.									

4.3.5. What have you done to face these crop constraints (see 4.3.4.)?

Crop name	Action done to face crop constraints
a.	
b.	
c.	
d.	

4.3.6. At which time in kharif do you have the most amount of work to do? Why? in which order do you deal with your crops?

Time in kharif 2013	YES / NO	Crops priority order:
Land Preparation	YES / NO	
Sowing	YES / NO	
Weeding	YES / NO	
Manure Application	YES / NO	
Fertilizer Application	YES / NO	
Harvest	YES / NO	
Threshing	YES / NO	

4.3.7. Crop operation RABI 2013

For your crops grown in rabi 2013, inform:

	Crop1	Crop2	Crop3	Crop4
When did you do your land preparation? (month, week)				
When did you sow? (month, week)				
When did you buy your fertilizers? (month, week)				
When did you buy your pesticides? (month, week)				
When did you weed ? (month, week)				
When did you harvest ? (month, week)				
When will you sell your crops?				

4.3.8. Crop constraints Found in RABI 2013

Crop name	Type of constraint								
	Seed defect	Late sowing	Delayed rain	Heavy rain	Long dry spell	weed	Disease	Pests	Animal Pressure
a.									
b.									
c.									
d.									

4.3.8.1. What have you done to face these crop constraints (see 4.3.8.)?

Crop name	Action done to face crop constraints
a.	
b.	
c.	
d.	

4.3.9. At which time in Rabi do you have the most amount of work to do? Why? in which order do you deal with your crops?

Time in Rabi 2013	YES / NO	Crops priority order:
Land Preparation	YES / NO	
Sowing	YES / NO	
Weeding	YES / NO	
Manure Application	YES / NO	
Fertilizer Application	YES / NO	
Harvest	YES / NO	
Threshing	YES / NO	

4.4. Concerning the location of the crops on the plot
From kharif 2013 to kharif 2014, precise which crop was grown in kharif 2013 at this place?

plot	Crop kharif 2013	Crop kharif 2014

From Kharif 2014 to Rabi 2014 precise which crop will be plant in Rabi 2014 at this place?

plot	Crop kharif 2014	Crop rabi 2014

4.5. Concerning the soil quality of your crop plots:

Do you have some crop plots:	YES / NO	Which crops to do like to grow on it?
More fertile	YES / NO	
Less fertile	YES / NO	
Close to tank/stream	YES / NO	
In coconut garden	YES / NO	
In tree shadow plots	YES / NO	

4.6. Concerning the location of your crops:

Do you prefer grow certain crop:	YES / NO	Which crops to do like to grow on it?	Why?
Closer to the road	YES / NO		
Closer to the house	YES / NO		

4.7. For your land preparation

4.7.1. How do you determine when to start land preparation?

- ☐ Same month/week every year (if so which month/week)
- ☐ After the start of first rain? (if so how many days after first rain)
- ☐ Based on groundwater availability (ground water level)
- ☐ Other

4.7.2. What is the gap (no of days) between harvest of kharif and sowing in rabi?

4.8. For your irrigation system

4.8.1. How do you determine when to irrigate?

- ☐ Fixed interval (once in a week or once in 10 days)
- ☐ Soil humidity inferior to ________
- ☐ Take in consideration the groundwater level
- ☐ Physical aspect of the plant
- ☐ No rain for ___ days
- ☐ You follow the manufacturer's recommendations (specify his name)
- ☐ You follow the agricultural technician advice (specify his name)

4.8.2. How do you organize the distribution of water among the different fields? (how do you define which field get irrigated first, second...)

- ☐ all the fields are irrigated the same day, the same way
- ☐ rotate irrigation between fields depending on the stage of the plant
- ☐ irrigate fields where the plant seems to need water

4.8.3. How do you determine the amount of water you apply?

- ☐ Same amount of irrigation for all crops
- ☐ Based on crop water requirement
- ☐ Based on crop type (commercial, self-consumption)
- ☐ Based on crop duration
- ☐ Based on water holding capacity of the soil
- ☐ Based on expected income crops

4.8.4. What crops have the highest irrigation priority?

- ☐ crop more sensitive to drought (**list the crops**…………………………………………….……..)
- ☐ higher expected income (**list the crops**…………………………………………………..)
- ☐ crops for self-consumption (**list the crops**…….……………………………………………)

4.8.5. What do you do if the water available in the borewell is decreasing and not enough to irrigate the whole irrigated land?

- ☐ Change frequency (be specific)
- ☐ Change quantity (be specific)
- ☐ Borrow water resource from a neighbor
- ☐ Change irrigation techniques (be specific)
- ☐ Stop irrigating
- ☐ Other (be specific)

4.9. For your fertiliser operations

4.9.1. Do you apply manure?

Crop kharif 2014		Crop rabi 2013	
	Yes / No		Yes / No
	Yes / No		Yes / No
	Yes / No		Yes / No
	Yes / No		Yes / No

4.9.2. How do you allocate farm manure to the different crops in kharif and rabi season?

- ☐ Equally distributed
- ☐ Depending on crop needs
- ☐ Depending on crop giving higher expected income
- ☐ Other (be specific)

4.9.3. Do you apply chemical fertilizer to each field? YES / NO

4.9.4. Do you adapt these applications to your soil characteristics? YES / NO

4.9.5. How do you determine the quantities and number of fertilization applications?

- ☐ It depends on the market price of fertilizer
- ☐ It depends on the availability of farm yard manure
- ☐ You follow the agricultural department advice(specify the name)
- ☐ You follow the manufacturer’s recommendations (specify the name)
- ☐ You decide based on your past experience
- ☐ Other (be specific)

4.9.6. What crops have the highest fertilization priority? Why?

priority	crop	reasons
1		
2		
3		
4		

4.10. For your pesticide operations

4.10.1. How do you determine the quantities and number of pesticide applications?

- ☐ You decide based on your past experience
- ☐ You follow the agricultural technician advice (specify his name)
- ☐ You follow the manufacturer's recommendations (specify his name)
- ☐ Decide based disease type

4.10.2. When do you decide to treat?

- ☐ do a systematic treatment (specify when, and plant stage)
- ☐ treat only if pest attack

4.11. What would you do if you were unable to sow the planned crop in time (e.g. because of erratic rains, late monsoon)?

- ☐ grow the next season crop (specify which one)
- ☐ grow a shorter season crop (specify which one)
- ☐ make a temporary fallow
- ☐ other (be specific)

4.12. What would you do if the crop does not come up well?

- ☐ Resow the same crop
- ☐ grow a shorter season crop (specify which one)
- ☐ keep it like it is
- ☐ make a temporary fallow
- ☐ other (be specific)

4.13. Residue management

- ☐ Not Managing
- ☐ Burn in the filed/Through out of field
- ☐ De-composting in the field
- ☐ Use for fuel
- ☐ Others

4.14. Does late or early monsoon influence your choice of crop to grow in kharif? YES / NO

4.15. In kharif, if the monsoon has been delayed, do you:

- ☐ Reduce your soil preparation
- ☐ Increase seed density
- ☐ Change crops for the season (specify which ones)
- ☐ Select short duration and resistant varieties

4.16. In rabi, if the rain in kharif has been good and the water level in the borewell is high, do you:

- ☐ Grow additional short duration cash crops (specify which ones)
- ☐ Increase the area of the higher expected income crops (specify % area increase)
- ☐ Don't change your usual crop sequence

4.17. In Rabi, if the rain in Kharif has been poor and the water level in the borewell is low, do you:

- ☐ Grow only less water requirement crops (specify which ones)
- ☐ Do Fallow
- ☐ Grow only higher expected income crops (specify which ones)
- ☐ Don't change your usual crop sequence
- ☐ Select short duration and resistant varieties

5. Perception / ressources / contraints

5.1. Market system and agro food chain

5.1.1. Where do you get your inputs (seeds, fertilizers, pesticides)?

inputs	Retailer/cooperative/company/government agro shop **(give name if possible)**
seeds	
fertilizers	
pesticides	

5.1.2.**Where do you sell your crops?**

	crops
Cooperative	
Marketing board(specify name)	
Local market	
Local agent	
Company	
Others (specify)	

5.2. Water

5.2.1.Borewell information

Sl No.	Farm location Number	Borewell installed year	Total depth of borewell	Working/Fail/yet to start	When was bore well failed	Motor fitted/Motor not fitted	Pump HP
1							
2							
3							

5.2.2.How many hours during the day is power supplied to your farm:

Total Hours …………. in kharif,

Total hours…………..in rabi

Total hours ………….in summer

5.2.3.Does your access to water limit the area that you cultivate in any season of the year? YES / NO

5.2.4.Does irrigation water availability affect your decision about the type of crop grown?YES/NO

5.2.5. what will you do if your borewell fails?

- ☐ Buy water
- ☐ Increase tank and rain water storage
- ☐ Change your crop choice (specify which crops to stop, new crops)
- ☐ Changes in irrigation system (changes in equipment)
- ☐ Get crop insurance
- ☐ Dig a deepper well
- ☐ Other (be specific)

5.2.6. Do you buy water? YES/NO **(if yes, from who?)**

5.3. Climate

5.3.5. Have you heard of climate change? YES / NO

5.3.6. **Have you identified current changes in climate?** YES / NO

5.3.7. What are the main climatic risks you have already encountered?

Climatic risks	kharif / rabi	year	Number of days	Adaptation code*
Flood	kharif / rabi			
Drough	kharif / rabi			
Delayed monsoon	kharif / rabi			
Wind	kharif / rabi			
High temperature	kharif / rabi			
Low temperature	kharif / rabi			
Rainy season end sooner	kharif / rabi			
Less rain	kharif / rabi			

* Change in crop variety=**1**, Decrease irrigation=**2**, Increase irrigation=**3**, Form pond construct=**4**, Dig new borewell=**5**, Stop irrigation=**6**, Reduce livestock=**7**, Keep improved livestock=**8**, Migration to other area=**9**, Lease out land=**10**, Purchase water=**11**, Plant shade trees=**12**, Change sowing time=**13**, Others=**14** (specify)

5.3.8. What would you change in your farming practices to face climate change?

Changes crops	YES / NO
Select more resistant varieties	YES / NO
Change sowing dates	YES / NO
Do more intercropping crops	YES / NO
Plant shade trees	YES / NO
Change your irrigation equipment	YES / NO
Migrate to other area	YES / NO
Get crop insurances	YES / NO
Diversify your crops (grow more crops but on smaller area)	YES / NO

1.2. The global survey in the Berambadi watershed

1.2.1. Questionnaire design

The questionnaire was divided into three parts on farming context, farm performances and farming practices and techniques. The first part of the questionnaire focused on household characteristics, farm structure, assets, partnerships, and farm objectives. After details about household organization, farm assets, and farm marketing position, we asked farmers about their performances and their practices over the past two years. In-depth questions were asked about irrigation, borewells, and rainfall. Since no records were kept from year to year, information about historical management went no further than two years in the past.

1.2.2. Sample selection

The farmer land ownership register (Bhoomi) of Karnataka provided the list of farmers per village in the watershed and the land ownership of farmers. 5461 farm households are listed on the watershed. To identify how many and which farms should be surveyed in this heterogeneous agrarian community, we used a purposive stratified proportional sampling method. This sampling procedure is used when the purpose of the research is to estimate a population's parameters. In proportionate stratified sampling, the number of elements allocated to the various strata is proportional to the representation of the strata in the target population. In our farmer population, we stratified the farmers based on the land ownership of farmers. That is, farmers were considered as small, medium or large owners. The size of the sample selected from each stratum per village is proportional to the relative size of that stratum in the farmer population. As such, it is a self-weighting and equal probability of selection method (EPSEM) sampling procedure. The same sampling fraction is applied to each stratum, giving every element in the population an equal chance to be selected. The resulting sample is a self-weighting sample. The samples were purposefully selected to represent the caste diversity in the region. In total 684 farm households had been interviewed from September 2014 to March 2015 on the watershed which represent 12.5% of the farm population.

1.2.3. Interview process

The enumerators were organized into four teams of two peoples. Interview process on the watershed was conduct village by village. The survey consisted in a face-to-face interview lasting two to three hours in the local language.

The aim of the project is to develop scenarios of water consumption by agriculture in changing climate. It is therefore necessary to understand farming practices that impact water use

Start the interview by describing the purpose of the survey: for academic research only, accurate answers are important and gratefully acknowledged, etc.

We are going to ask you some questions about your farm, the way you organise your production, the source of information you use, and about yourself and the family members involved in production. All is which will be treated confidentially.

1. Basic Information

1. Name of Village_______________________

2. Panchayat Name___________________________

3. Household Number _______________________

4. Name of household head _________________________

5. Respondent Name________________________________

6. Caste__________________________________

6. Interviewer _____________________________________

7. Date__________________

8. Interview start time ______________ Interview End time___________

2. Household Information:

2.1 How many members presently residing in the home? _______

Sl.	Name	Relation with HH head	Gender	Age in years*	Education	Occupation**		Training on farm activities	Training on dairy activities	Income form off-farm activity
						Primary	Secondary			
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

* For a child below one year code is **0**

Relationship code:

Head=**1**, Wife/Husband=**2**, Son/Daughter=**3**, Grandchild=**4**, Father/Mother=**5**, Sister/Brother=**6**, Niece/Nephew=**7**,Uncle/Aunt=**8**, Son/Daughter-In-Law=**9**,Father/Mother-In-Law=**10**, Brother/Sister-In-Law=**11**, Grandparent=**12,** others=**13**

Education code:

Illiterate=**1**, Read and write=**2**, Pre-Primary School (1-5)=**3**, Upper primary (6-8)=**4**, High School (9-10)=**5**, PUC - (11-12), Diploma Course=**6**, Graduation=**7**, Post-Graduation and above=**8**, Technical Degree (medical, engineering, agriculture, etc.)=**9**, Other professional courses (TCH/Bed/Med)=**10**

****Occupation code:**

Own agriculture work=**1**, Agriculture labour=**2**, Petty business=**3**, Dairy farming=**4**, Plantation worker=**5**, NTFP collecting=**6**, Livestock grazing=**7**, Factory worker=**8**, Pension earner (social security/Job pension)=**9**, Rural crafts (carpentry, blacksmith, pottery, weaving, goldsmith, basket making, leather work, etc.)=**10**, Government job=**11**, Commission agent=**12**, Contractor=**13**, Quarry worker=**14**, Bee keeper=**15,** Student=**16**, Domestic work (cleaning, cooking, water fetching, child care, fire making, washing clothes, etc) =**17**, Driver=**18**, Not working (Children/Aged/physical disable/illness etc.)=**19**, Mason= **20**, Other=**21** (specify)

2.2. Manpower

1. How many family members work permanently on the farm, including yourself? ________ Persons

2. How many family members work temporary on the farm, including yourself? _______ Persons

3. Do you have permanently workers (that are not family members) on your farm? **Yes/No.** If yes, number of ______Persons

4. Did you hire temporary workers on the farm during the last year? **Yes/No**. if yes, number of ________persons

5. At what wage were they paid/day Male Worker Rs._______Day Female worker Rs.__________Day

6. Were you helped by neighbours during the last season? **Yes/No.** if yes number of___________ Persons and Number of days helped_________

7. How many family members working as agriculture labours(2013)?________________

8. Approximate labour work days in a week

1. kharif :
2. rabi :
3. summer :

9. Number of month work days in a Season

1. kharif :
2. rabi :
3. summer :

10. Any of your family members temporarily migrating (2013)? Yes/No

If yes,

1. Period of migration______________
2. Place of Migration_________________
3. Nature of work did during migration________________
4. Total net savings from Migration_____________________

2.3. Skill Manpower

1. Did you or member of your family receive any training on farm activities? **Yes/NO** if yes, Number of days/week/month/years of training taken--------------

1. a. Date of the last training____________

2. Did you or member of your family receive any training on dairy activities? **Yes/NO** if yes, Number of days/week/month/years of training taken---------------

2. a. Date of the last training ____________

3. What institution was in charge of the training?

3.1 Farm Related	**3.2 Dairy related**
a. Agricultural University	**a.** Agricultural University
b. Agriculture department	**b.** NGO
c. Horticulture department	**c.** Milk co-operative societies
d. NGO	**d.** others
e. Farm companies	
f. Farm co-operative societies	
g. Others	

4. Did the training include

1. Land preparation
2. Crop choice
3. Fertiliser use
4. Irrigation
5. Seed management and selection
6. Extreme weather management
7. Others, specify ………………..

5. Did you find the training useful

0. No
1. Yes

If no, specify …………………………………………………………………………………….

6. Integration in farmer networks and source of information

a. Are you part of a farmer network?

0. No
1. Farmer union (identify it)
2. Cooperative (name it and locate it)
3. Other, specify

b. What are your main sources of information?

0. No information needed
1. Cooperative (name it and locate it)
2. Extension services (name and locate it)
3. Agricultural school or institute (name it and locate it)
4. Farmer union (name it and locate it)
5. Agricultural retailers (name and locate it)
6. Family and friends
7. Other farmers
8. Press and media
9. Other, specify …………………………

c. Formal institutional membership network

1) Member in SHG Y/N M/F Number of persons _________

2) Member in Dairy Farm Y/N M/F Number of persons _________

3) Member in SDMC Y/N M/F Number of persons _________

4) Member in JFPM Y/N M/F Number of persons _________

5) Member in JSYS (TWUA) Y/N M/F Number of persons _________

6) Member in NREGP Y/N M/F Number of persons__________

7) Any other membership (specify) ____

d. informal institutions Networks

1. farmer-to-farmer extension Yes/No

2. Number of Close Farmers________

e.Trust Index

1. "Most farmers who live in this village can be trusted."

a. Do trust = 1
b. Do not trust =0

2. Do you think over the last few years this level of trust has gotten better, gotten worse, or stayed about the same?
   a. Better =2
   b. The same= 1
   c. Worse=0

f.Cooperativeness

Cooperativeness in this study can be understood degree to which a Farmers share mutual labour, Farm equipments, Rapier farm roads,

1, sharing mutual farm Labour

2. Not sharing mutual farm labour
3. Sharing farm equipments
4. Not sharing farm equipments
5. Repair farm road mutually
6. Not repair farm road mutually

g. Do you use external information (if any) in your decisions?

0. No, they are not useful

1. Yes, partly

3. Farm assets

Material type	**Use/Not use**	**Owned=1 rent=2***	**Cost (purchase and rent/day/hour)**	**Loans taken?**
Wooden plough	Y/N			
Iron plough	Y/N			
Tractor drawn cultivator	Y/N			
Seeder	Y/N			
Weeder	Y/N			
Pesticide sprayer	Y/N			
Wheel barrow	Y/N			
Treshing machine	Y/N			
Organic manure pit	Y/N			

3.1 Please Fill the Below Table

Plot ID	B.30. Tractor/bullock used on this plot 0. None 1. own tractor 2.rented tractor 3. owned bullock 4. rented Bullock	B.31. Number of hours used on this plot last season				
		1. For tilling	For spraying manure, fertilizers, pesticides	3. For carrying harvest	4. For other	5. Total

4. Livestock Information:

Type*	Number	Present value	Reasons for keeping**	Income per year(2013)
1.				
2.				
3.				
4.				
5.				
6.				
7.				

*Bulls=1, oxen=2, cow=3, buffalo=4, sheep=5, goat=6, poultry=8, pig=9
**own cultivation/Hiring out=1, manure=2, fuel (cooking) =3, milk=4, meat=5, egg=6

4. A. How do you manage manure from cattle?

0. No particular management
1. Use on land
2. Give or sell to others
3. Fuel (cooking)

4. B. Did our cattle stock change since last year?

0. No
1. Increased: ……… animals
2. Decreased: … …animals

5. General Farm Characteristics:

1. Do you have Farm Land? Yes No
2. In how many places your farm lands located? (Including lease in/Share cropping land_________
3. Total Rainfed land__________ (Acre)
4. Total irrigated land_________ (Acre)

5.1. Specific Farm Characteristics:

a. Number of farms in different location and location identity	One( )		Two ( )		Three ( )		Four ( )	
b. Farm Size (in acre)								
c. Farm ownership	Own/Lease /Share		Own/Lease/ Share		Own/Lease /Share		Own/Lease/ Share	
d. Source of ownership of your own farm	Parents/Purchase/Gift/Government		Parents/Purchase/Gift/Government		Parents/Purchase/Gift/Government		Parents/Purchase/Gift/Government	
e. From how many years do you operate the farms								
f. Is there any change in farm size over the last five years	Increase/Decrease/Same		Increase/Decrease/Same		Increase/Decrease/Same		Increase/Decrease/Same	
	If yes, How many acres?		If yes, How many acres?		If yes, How many acres?		If yes, How many acres?	
g. Farm soil type								
h. Farm Buildings	Farmhouse	Pump house	Farmhouse	Pump house	Farmhouse	Pump house	Farmhouse	Pump house
h.1. No of buildings	One/two/ three	One/two/ three	One/two/ three	One/two/ three	One/two/ three	One/two/ three	One/two/ three	One/two/ three
h.2. Recently constructed farm building (mention year)								
h.3. Oldest farm building(mention year)								
i. Farm distance from your home in Km								
j. Is farm has irrigation source?	Yes/No		Yes/No		Yes/No		Yes/No	
k. ownership of irrigation source(Own/Joint/Neighbor/Government)								
l. Irrigation method of each farm	Flood/Furrow/Sprinkler/ drip		Flood/Furrow/Sprinkler/ drip		Flood/Furrow/Sprinkler/ drip		Flood/Furrow/Sprinkler/ drip	
m. Do you have farm pond/Farm tank?	Yes/No		Yes/No		Yes/No		Yes/No	
n. Water Source for Pond/farm tank	Own well/Rainwater		Own well/Rainwater		Own well/Rainwater		Own well/Rainwater	
o. How many hours it take to fill?								

5.2 What changes made in farm investments, farm size and crop pattern from past 5 years? And why?

a. Machinery investment?
b. Livestock investments?
c. Irrigation investment and uses?
d. Other infrastructure investments?
e. Changes in land preparation?
f. Introduction of new crops? Stop others? (e.g. Marigold)
g. Increase or decrease cropping land area?

5.3 General objective of farm

5.3. A. What would you say the general objective of your farm is

1. Earn a livelihood for my family
2. Maintain the farm in the family
3. I prefer farming to any other activity

5.3. B. Would you say your farm has an adequate size?

1. Farm is too small
2. Farm is Medium
3. Farm is too big

5.4 Crop management

a. Do you follow a crop pattern defined over several years? Y/N

If yes, which one:.........

b. Which crops do you try to grow each year and why?

Cash crops:
Self-consumption crops:

5.5 Cropping and Marketing information

Year 2014

Plot ID	5.5.1.Crop planted this season 2014 KHARIF Crop code (see appendix)	Acres	5.5.2. Crop to be planted this season 2014 RABI Crop code (see appendix)	Acres	5.5.3. Crop to be planted this season 2015 SUMMER Crop code (see appendix)	Acres

2013KHARIF

Plot ID	5.5.4. Crop planted in 2013 Crop code (see appendix)	5.5.5. Was the crop successful? 1. Yes 0.No, specify ……	5.5.6. Quantity harvested	5.5.7. Unit	5.5.8. Price received (RS / ton or kg)	5.5.8. a. Price received (more/expected/Less	5.5.9. Sold to whom(specify name) 0. Used on farm 1. Cooperative (specify name) 2. Marketing board(specify name) 3. Local market (specify name) 4. Other, specify

2013 RABI

Plot ID	5.5.10. Crop planted in 2013 Crop code (see appendix)	5.5.11. Was the crop successful? 1. Yes 0. No, specify ……	5.5.12. Quantity harvested	5.5.13. Unit	5.5.14. Price received (RS / ton or kg)	5.5.14. a. Price received (more/expected/Less	5.5.15. Sold to whom 5. Used on farm 6. Cooperative (specify name) 7. Marketing board(specify name) 8. Local market (specify name) 0. Other, specify

2013 SUMMER

Plot ID	5.5.16. Crop planted in 2013 Crop code (see appendix)	5.5.17. Was the crop successful? 1. Yes 0.No, specify ……	5.5.18. Quantity harvested	5.5.19. Unit	5.5.20. Price received (RS / ton or kg)	5.5.20. a. Price received (more/expected/Less	5.5.21. Sold to whom 9. Used on farm 10. Cooperative (specify name) 11. Marketing board(specify name) 12. Local market (specify name) 0. Other, specify

2012KHARIF

Plot ID	5.5.22. Crop planted in 2012 Crop code (see appendix)	5.5.23. Was the crop successful? 1. Yes 0. No, specify ……	5.5.24 Quantity harvested	5.5.25. Unit	5.5.26 Price received (RS / ton or kg)	5.5.27 Sold to whom (specify name) 13. Used on farm 14. Cooperative (specify name) 15. Marketing board(specify name) 16. Local market (specify name) 0. Other, specify

2012 RABI

Plot ID	5.5.28. Crop planted in 2012 Crop code (see appendix)	5.5.29. Was the crop successful? 1. Yes 0. No, specify ……	5.5.30. Quantity harvested	5.5.31 Unit	5.5.32 Price received (RS / ton or kg)	5.5.33 Sold to whom(specify name) Used on farm 17. Cooperative (specify name) 18. Marketing board(specify name) 19. Local market (specify name) 0. Other, specify

2012 SUMMER

Plot ID	5.5.34. Crop planted in 2012 Crop code (see appendix)	5.5.35. Was the crop successful? 1. Yes 0. No, specify ……	5.5.36. Quantity harvested	5.5.37. Unit	5.5.38. Price received (RS / ton or kg)	5.5.39 Sold to whom(specify name) 20. Used on farm 21. Cooperative (specify name) 22. Marketing board(specify name) 23. Local market (specify name) 0. Other, specify

5.6 Farm Technical operations

Please fill the graph below (2013 cropping season)

For each crop, place the main operations

- land preparation (e.g. ploughing, hoeing, etc)
- sowing (indicate density)
- fertilizer including manure (indicate amounts of manure, quantity of N, P, K or of product in that case give the name of the brand)
- pesticides (indicate quantity and specify reasons and type of pesticide)
- irrigation (volume apply in m3 or hours)
- harvest

Indicate any unexpected constraints such as a decease, animal pressure, erratic rains, and drought

Indicate period of work peak

	April	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
KHARIF crops												
Ex :												
RABI crops												
SUMMER crops												
Work peak (hours and number of people needed)												

Please fill the graph below:

	May	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mars**	**April**	**May**
Indicate when decisions are made, and information received													
information on input prices													
information on output prices													
Information on electricity price													
Establish contract with cooperatives													
select crops for kharif													
select crops for rabi													
select crops for summer													
buy seeds for kharif													
Buy seeds for rabi													
Buy seeds for Summer													
Define time-window to saw in kharif													
Define time-window to saw in rabi													
Define time-window to saw in summer													
Buy fertilizers													
buy pesticides													
sell outputs													

5.6. A. For your sowing:

How do you determine when to start land preparation/sowing?

1. After the start of first rain? (if so how many days after first rain)
2. Based on groundwater availability (ground water level)
3. Same month/week every year (if so which month/week)
4. What is the gap (no of days) between harvest of kharif and sowing in rabi?

5.6. B .For your irrigation system

a. How do you determine when to irrigate?

1. No rain for....days
2. Fixed interval (once in a week or once in 10 days
3. Soil humidity inferior to....
4. Take in consideration the groundwater level
5. Physical aspect of the plant
6. You follow the manufacturer's recommendations (specify his name)
7. You follow the agricultural technician advice (specify his name)

b. How do you organize the distribution of water among the different crops? (how do you define which field get irrigated first, second...)

c. To which crops is irrigation uppermost assigned? Why?

1. Higher expected income
2. Crop more sensitive to drought
3. Crops for self-consumption

5.6. C. For your fertiliser operations,

a. How do you determine the quantities and number of applications?

1. You follow the manufacturer’s recommendations (specify his name)
2. You follow the agricultural technician advice (specify his name)
3. You decide based on your past experience
4. It depends on the market price
5. It depends on the availability of farm yard manure

b. Do you adapt these applications to your soil characteristics?

To which crops is fertilization uppermost assigned? Why?

1. Higher expected income
2. Order of priority of crops (1. Turmeric, 2. Sunflower ….. Etc)

c. Do you make side dressing fertiliser applications?

0. No
1. Yes

5.6. D. For your pesticide operations,

a. How do you determine the quantities and number of applications?

1. You follow the manufacturer’s recommendations (specify his name)
2. You follow the agricultural technician advice (specify his name)
3. You decide based on your past experience
4. Decide based decease type

b. For your fertiliser and pesticide operations, do you decide according to the aspect of leaves, soil… 0. No

1. Yes

c. How do you manage pest?

1. Spraying pesticide
2. Planting pest control plants
3. Early sowing crops (mature before pest attack starts)
4. Removing decease plants
5. Not taken any action

5.6. E. For the choice of your crops (rank here)

1. The price you expect is the leading factor (max profit, secure profit, repay loan (ST/LT), children's education?)
2. The market for the crop is more accessible/crop easier to sell
3. You are used to grow these crops
4. Crop choice is made according to water availability
5. Crop choice depends on input costs
6. Crop choice depends on labour available (minimize working hours?)
7. To meet household food grain needs
8. To produce livestock grain
9. Need for diversification

5.6. F. For the choice of the plots where to grow the wanted crops (rank here)

. 1. Proximity to roads
2. Irrigable characteristic of the plot
3. Soil characteristics
4. Passed crop
5. Use to grow this crop at a certain place

a. What would you do if you were unable to sow the planned crop in time (e.g. because of erratic rains, late monsoon)?

1. Change crop (which one, and why?)
2. Make a temporary fallow
3. Grow a shorter growth crop

b. What would you do if the crop does not come up well?

1. Change crop (which one, and why?)
2. Make a temporary fallow
3. Grow a shorter growth crop
4. Keep it like it is

C. Residue management

0.No
1. Leave on the farm
2. Cut and carry for cattle
3. Other, specify

5.6. G. Market system and agro food chain

These questions deal with your relationship with suppliers of agricultural inputs and buyers of your products

a. Where from you buy agricultural inputs ?(fertiliser, pesticide, seed)

1.From a retailer
2. from a cooperative
3. Other, specify

b. Indicate your expenditures on the following inputs for the previous season and for all your crops

Inputs	Value (RS)	Finance source (own saving=1,Crop loan=2,Hand loan=3,Business income=4,Dairy income, Loan from farm company=5,Loan from merchants=6, others=7	Quantity	Unit (kg, etc.)
1.Seed				
2.Fertiliser				
3.Pesticide				
4.Veterinary				

c. In general, you sell your production to
1. A marketing board (name it and locate it)
2. A cooperative (name it and locate it)
3. Another type of buyer (name it and locate it)
4. A local market (name it and locate it)
5. Other, specify ……………….

d. Do you feel free to decide where to sell
0. No
1. Yes

e. In deciding where to sell
1. A high expected price is the leading factor
2. I can sell more of my production
3. I can have a guaranteed price
4. I have more interesting input prices when I sell to the same agent

f. Do you have a contract with a marketing board or a cooperative/company?
0. No
1. Yes

g. If yes, do you have a guaranteed price before growing the crop
0. No
1. Yes

h. If yes, what part of your total agricultural revenue is coming from such a contract
1. Less than 1/4
2. between 1 /4 and 1/2
3. More than ½

i. Access to credit and level of indebtedness

SL. No	Year	Sources of Loan	Amount of loan taken	Purpose of loan taken	Repaid	Remark
1						
2						
3						
4						

Section 3. Natural capital

[Only applicable for farmers with irrigated land]

6. Borewell Information:

Sl No.	Farm location Number	Borewell installed year	Total depth of borewell	Working/Fail/yet to start	When was bore well failed	Total Cost of each failed borewell	Total Cost of working borewell (except pump cost)	Motor fitted/Motor not fitted	Pump HP	Pump Purchase year	Pump Price	Finance source for bore well(Own savings=1, Loan taken on Gold=2, Hand loan on Interest=3,Land leaseout=4, Livestock sold=5, Bank crop loan=6, Gangakalyan Yojana=7, Relatives/Friends=8(tick three main sources)
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												

6. A. When was the last repair made? ________________________________

6. B. What kind of repair made? _____________________________________

6. C. How much money spent for repair? _____________________________

6.2. Factors that force farmer to go for multiple borewells/Re-bored/digging new borewell

1, Capable to manage financial Burden- **Yes/No**

2. Misleading by local water diviner/Borewell agents/Friends and relatives - **Yes/No**

3. Gut feeling of farmers that he certainly getting water/god shake- **Yes/No**

4. Less aware/No awareness of geological condition of the area- Yes/**No**

5. Deeper borewell may be getting water--- **Yes/No**

6. Want to irrigate more crop area/to bring rainfed land into irrigation **---Yes/No**

7. Neighboring farmers owning multiple borewells-------Yes/No

8. Want grow more commercial crops----**Yes/No**

9. Limited hour supply of electricity hence one borewell not sufficient for irrigation—**Yes/No**

10. Low water in existing borewell/other problem in existing borewells (not deep, Boulders etc) **Yes/No**

6.3. Farmer's satisfaction over working borewells:

Working Borewells	Satisfied	Not Satisfied	Some how ok	Reason for not satisfied(Low discharge=1, Frequent Repair=2, Stop working in summer=3, water quality not good=4, Motor burn frequently=5, Problem in bore hole=6, Low pump capacity=7(tick three main reasons)
1				
2				
3				
4				
5				
6				

6.3. A. How many hours during the day is power supplied to your farm**:**

Total Hours …………. in kharif

Total hours………. in rabi/summer

6.3. B. How many time power shut down during specified time of three phase power supply?

____

6.3. C. Does your access to water limit the area that you cultivate in any season of the year? **Yes/No**

If yes, how much area really limits among total irrigable area(2013)? In

1. Kharif :
2. Rabi :
3. Summer :

6.3. D. Does irrigation water availability affect your decision the type of crop you grow**?** **Yes/No**

If yes, which crop you give the priority?

1. _______________
2. _______________
3. _______________

6.4. E. If Irrigation water availability not affects your decision of crop selection, which crops give the priority?

1. _______________
2. _______________
3. _______________

7. Possible adaptations/leeway to face Climate Change

To be asked necessarily after characterization of current practices (otherwise risk of bias)

To be discussed: Open or multiple choice questions ? (Proposal: open question, but possible answers "a priori" are proposed in dotted boxes: if the farmer has no idea, propose a list of these possible choices)

7.1. Adaptations to encountered climatic risks

A.1 What are the main climatic risks you have already encountered? Specify in which season and for how long

1. Flood, 2. Drought, 3. Delayed monsoon, 4. Wind, 5. High temperature, 6. Low temperature, 7. Other (specify)

A. 2 What do you change in your practices when such events occur?

(***Possible Changes***

1. Crop choice, 1.a crops discarded (specify), 1.b. new crops (specify)

2. Cropping calendars (2.a.sowing dates, 2.b late or early maturing crop varieties depending on the available growing season)

3. Irrigation management: 3.a amount, 3.b timing,

4. Cropping systems redesign (4.a. crop rotation, 4.b intercropping, 4.c multi-storey cropping, 4.d inclusion of perennial in dry lands, 4.e other (specify).

5. Changes in irrigation system, 5.a Changes in equipment

6 Water conservation or harvesting practices: 6.a Conservation furrows, 6.b micro catchments for tree systems, 6.c Conservation tillage, 6.d crop residue management, 6.e Other (specify)

7. Crop insurance

…)

A.3 What are the main climatic risks you fear ?

1. Flood, 2. Drought, 3. Delayed monsoon, 4. Wind, 5. High temperature, 6. Low temperature , 7. other (specify)

7.2. Farmers perception of Climate change

A.4 Have you heard of climate change?

0. No
1. Yes

A.5 what changes are you excepting due to climate change?

1. Flood, 2. Drought, 3. Delayed monsoon, 4. Wind, 5. High temperature, 6. Low temperature , 7. other (specify)

7.3. Quick description of expected climate changes

More accurate bibliographical review needed

Warmer conditions (around +2°C in annual mean), reduced amount of rainfall annually, during kharif season (-5%, June-Sept) during rabi season (-23% Jan--Feb) , uncertainties on the possible increase of drought (daily rainfall < 2.5 mm for 40 or more contiguous days) frequency in Rabi season (September-February)

NB : HadCM3 model , inconsistency between table 2.5 and fig 2.8, contrasted results on Mysore districts for drougth frequency (fig 2.10)

Slightly delayed monsoon, less precipitation in summer (Asfaq 2009 cited in AICHA introduction slides)

Consequences on crops : phenology, water availability ?

(http://www.metoffice.gov.uk/climate-change/policy-relevant/obs-projections-impacts)

7.4. Leeway- possible adaptations

A.6 what would be the problems encountered in case of climate change scenario?

A.7 what would you change in your farming practices to face climate events due to climate change?

(***Possible Changes***

1. Crop choice, 1.a crops discarded (specify), 1.b. new crops (specify)

2. Cropping calendars (2.a.sowing dates, 2.b late or early maturing crop varieties depending on the available growing season)

3. Irrigation management: 3.a amount, 3.b timing,

4. Cropping systems redesign (4.a. crop rotation, 4.b intercropping, 4.c multi-storey cropping, 4.d inclusion of perennial in dry lands, 4.e other (specify).

5. Changes in irrigation system, 5.a Changes in equipment

6 Water conservation or harvesting practices: 6.a Conservation furrows, 6.b micro catchments for tree systems, 6.c Conservation tillage, 6.d crop residue management, 6.e other (specify)

7. Crop insurance

…)

A.8. what would be impossible to change? Why?

Appendix 1: crop codes

1	Marygold
2	Horsegram
3	Turmeric
4	Onion
5	Watermelon
6	Beetroot
7	Maize
8	Jowar
9	Ginger
10	tsinees
11	Ragi
12	Sunflower
13	Coconut
14	Vegetables
15	Beans
16	Benise
17	Tomato
18	Carrot
19	Bengalgram
20	Banana
21	Cotton
22	Cowpeas
23	Redgram
24	Cabbage
25	Chilly
26	Garlic
27	Paddy
28	Potato
29	Sugarcane
30	Castrot
31	Groundnut
32	Brizal
33	Arese
34	Feildnet

2. Retailers and panchayat surveys

We surveyed seed retailers and Panchayats (village leaders) to learn about recommended crop management practices and village organization.

KANNEGALA
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

GOPALPURA
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

BERAMBADI
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

CHANAMALLIPURA
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

MADDUR

How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

MADDUR COLONY

How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

BECHANAHALLI

How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

CHANNAMALLIPURA

How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

LAKKIPURA
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

KUNAGAHALLI
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

KALLIPURA
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

HONNEGOWDANAHALLI
How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

BEEMANABEEDHU

How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

KUTHANUR

How many farm labors are available in your village?

Man labor	
Woman labor	

How many tractors (+cultivator), bullocks, seeder, weeder, threshing machine can be hired in your village?

Tractor + cultivators	
Bullocks	
Seeder	
Weeder	
Threshing machine	

GENERAL QUESTIONS TO SEED RETAILERS

SEED COMPANY – Gonga Kaveri, AVT (marigold), MAICO

FERTILIZER COMPANY – DIP, AVT

PESTICIDE COMPANY – ROGER, TRYPSIL, AVT, RACKET, HEADLINE

Crop name	Soil preparation	Sowing	Fertilize	Pesticide	Weed	irrigation	Soil management	Harvest
	Period: #: Comments:	Period: Density: Plant to plant: Row: Deth:	Manure 1st: Q1: 2nd: Q2: Chemical 1st: Fert1: Q1: 2nd: Fert2: Q2: 3rd: Fert3: Q3: 4th: Fert4: Q4:	Pest 1: Pesticide 1 : Q1 : Pest 2: Pesticide 2 : Q2 : Pest 3: Pesticide 3 : Q3 : Pest 4: Pesticide 4 : Q4 :	1st : 2nd : 3rd :	1st : Q1 : 2nd : Q2 : 3rd : Q3 : 4th : Q4: 5th: Q5:	Earthing up: Thinning:	Days: Signs:

Comments:

3. <u>Experimental plots</u>

Additionally, 52 experimental plots were monitored over three years (2011-2012-2013) (Figure 4), which provided observed quantitative data about crop production and crop management (Table 1). These data helped supplement the verbal information provided by farmers during surveys.

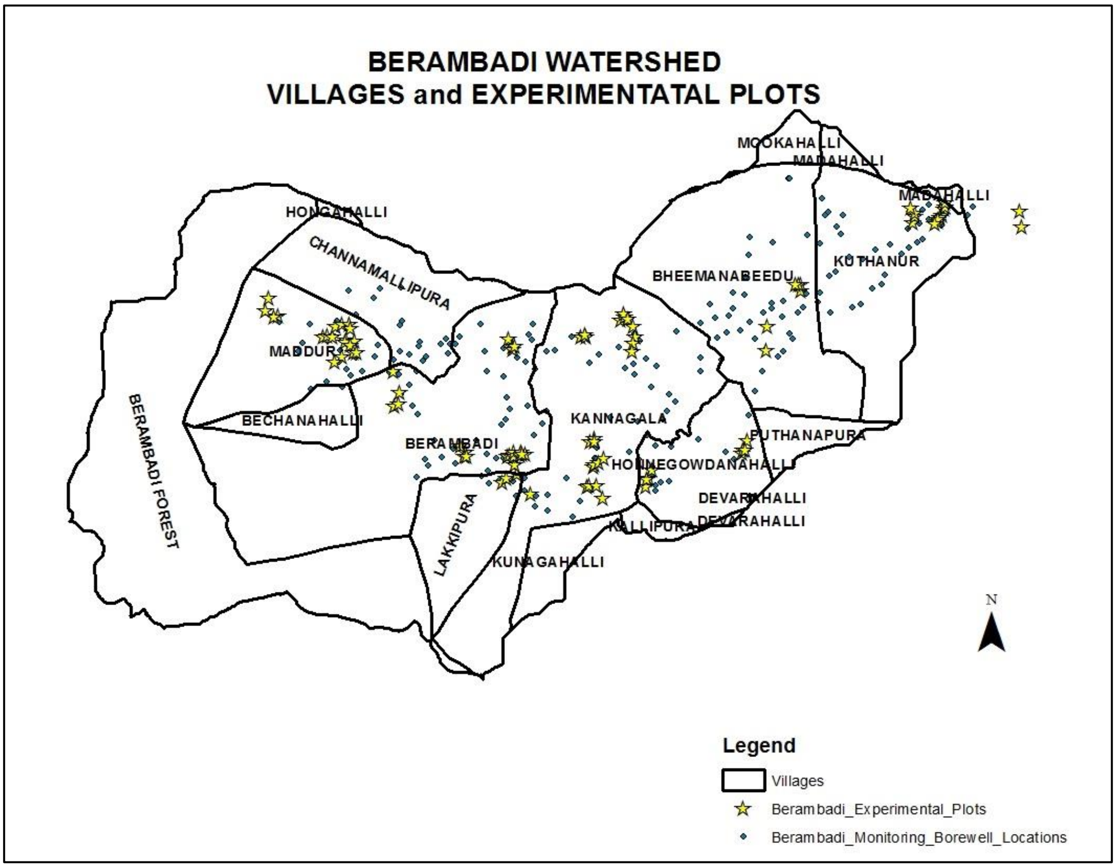


Figure Appendix 2. 5 Location of the experimental plots

Table Appendix 2. 1 Variable list

Village name	Contract Harvest Cost	Harvest month of main Crop code
Plot Number	Fertilizer Type	inter crop Yield- (Q)
Respondent name	Quantity Applied (kg)	Sold Price
Contact number	Total Fertilizer cost	main crop yield (Q)
Number of Plots	FYM (Tractor)	Sold price/Q
Plot area in Acre/Gunta	Cost of FYM	Type of Irrigation
Plot Area (in acre/Cents)	Pestcide-Type	Seedling method Row to Row (infeet) Note:Intercrop only
Crop year	Pestcide quantity	Seedling method Depth in inches)Note: Intercrop only
Season	Cost of Pesticide	Seedling method Row to Row (infeet) Note:Main crop only
Name of the crop	No of Traction (Tractor)	Crop Verity (intercrop)
Crop area in Acre/Gunta	Tractor Traction cost (if own) (liters of disel used)	Crop verity (maincrop)
Crop area (in acre/cents)	Tractor Traction cost in rupees (if hired)	Number of Irrigations given (inter crop only)
Sowing Month	No of Traction- (Bullock pair)	Irrigation Intreval (in days) (Intercrop only
Sowing week	Traction cost of Bullock	Number of Irrigation (Main crop only)
Labor-male	intensityPest Problem Code	Irrigation interval (in days) Main crop only
Labor-Female	No of time Weed remove	Seed/plant used in Q(intercrop)
Total labors	Intensity of weed Problem code	Cost of Seed/plant(intercrop)/Q
Total labor cost (only hired labor)	Harvest Month of inter crop code	

4. Meteorological data

Meteorological data were obtained from a meteorological station and water gauges installed on the watershed.

5. Price and cost data

Prices and costs were obtained from farmers and from official district data from the Indian Ministry of Agriculture and Cooperation (Directorate of Economics and Statistics) and the National Informatics Center (Agricultural Census Division).

Appendix 3: Conceptual model and Ontology

This appendix aims at providing details on the UML representation of farming system in the Berambadi watershed (Figure Appendix 3.1) obrained with the CMFDM methodology.

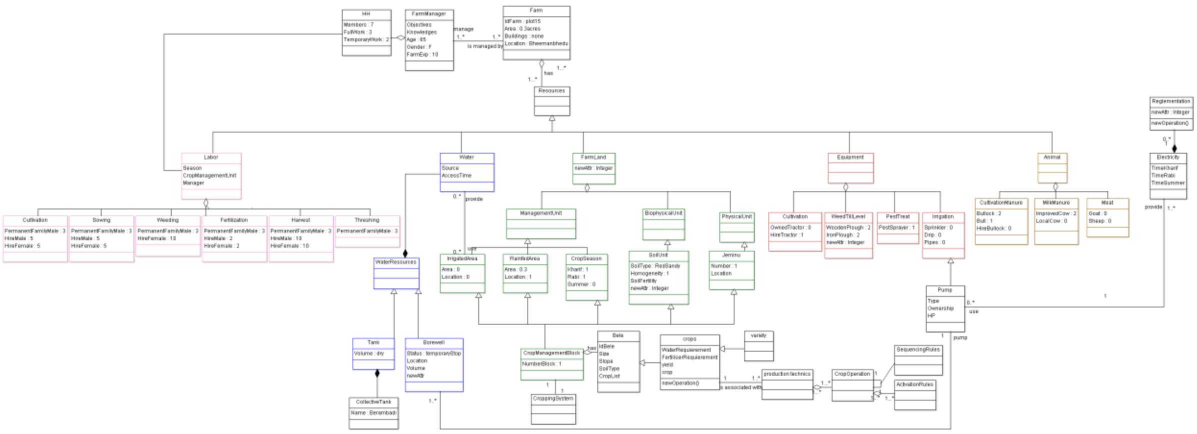


Figure Appendix 3. 1 UML representation of farming system in the Berambadi watershed

First we have a farm with specific characteristics that is managed by a farm-manager who belong to a household. This farm has several ressources : its labor, its water resource, its farmland, its equipment, its animals and have access to electricity (4 to 6 hours depending on the season and distributed in 3 phases) (Figure Appendix 3.2).

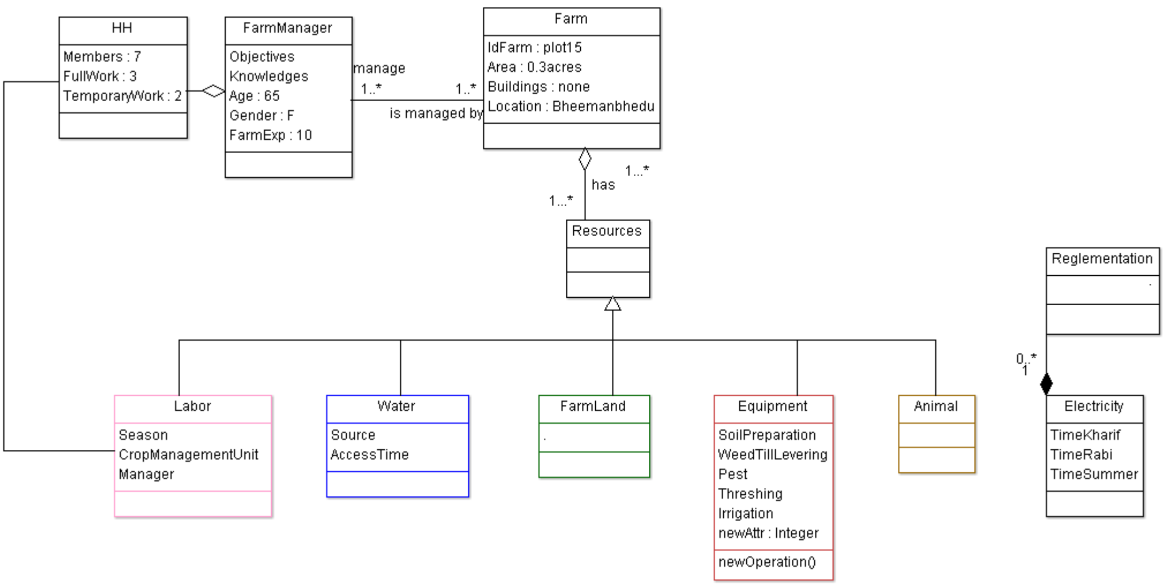


Figure Appendix 3. 2 Zoom on farming system representation

Looking in more details to the labor resource (Figure Appendix 3.3), need for labor varies with the season (more important in kharif than rabi or summer), the crops grown and the crop management operation concerned. For instance, the harvest is in general the operation that requires more labor in the season. The labor can be permanent or temporary. Permanent labor refers to family members working on the farm as primary activity, or permanent employees. Temporary labor can be mutual labor from a neighbor, family members working on the farm as a second activity, hired persons. Farmer can contract a group of labor by field work or hire individual labor (payed per day). The temporary hired labor comes from the village and neighbor villages (people looking for jobs because of monsoon onset delay, or other climatic events impacting on their own crop production) and represent a limited labor resource, so that when one farmer hires labor, the other farmers have less labor available which can constrain them to delay their operations.

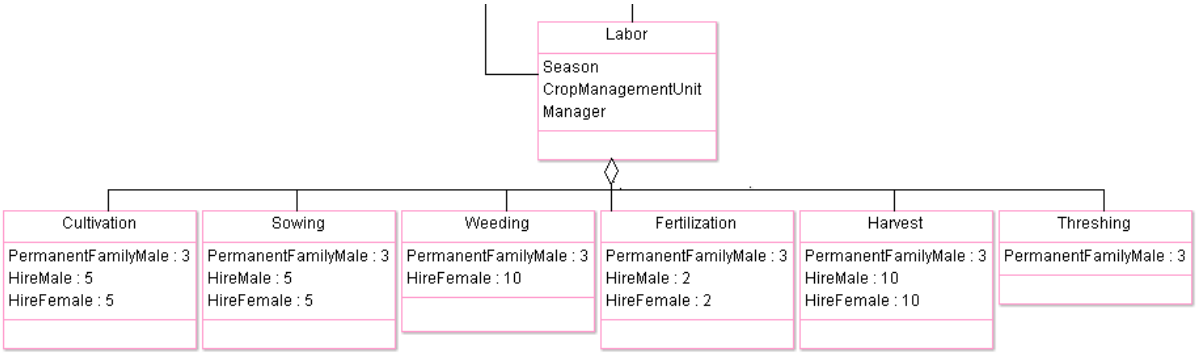


Figure Appendix 3. 3 Zoom on labor organization.

The water resource is defined by the sources of the water dedicated to irrigation, its storage capacity, and depends on access to electricity (see Figure Appendix 3.4).

Water sources can be collective like tanks or individual like wells and borewells. Farmers may store some water from pumping groundwater or rainfall with individual ponds.

Ground water irrigation volume depends on the borewell status (depth, working, temporary stop, failed), the pump power, the pipe diameter, and the electricity. With numerous power cuts during the specified time of three phase power, farmers prefer using automatic pumps that start as soon as electricity goes back on. This feature makes the estimation of water used for irrigation difficult..

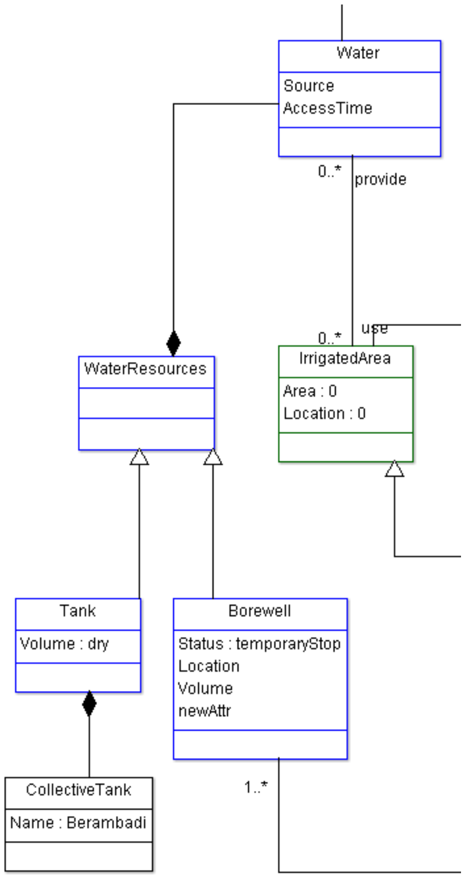


Figure Appendix 3. 4 Zoom on water resource

Most of the farmers on the watershed own their farm land. Three main unit are identified (Figure Appendix 3.5): 1) management unit caracterized the type of land from an irrigated access point of view; 2) biophysical unit distinguished area by their soil type, 3) physical unit distinguished area by their physical location in terms of jeminu. Notice that another unit could be distinguished, temporal unit that distinguished area basically on the time operation is executed on the land. Crossing these units, management blocks can be identified with specific cropping systems. Each block is composed of plots or beles where a unique crop is grown each season.

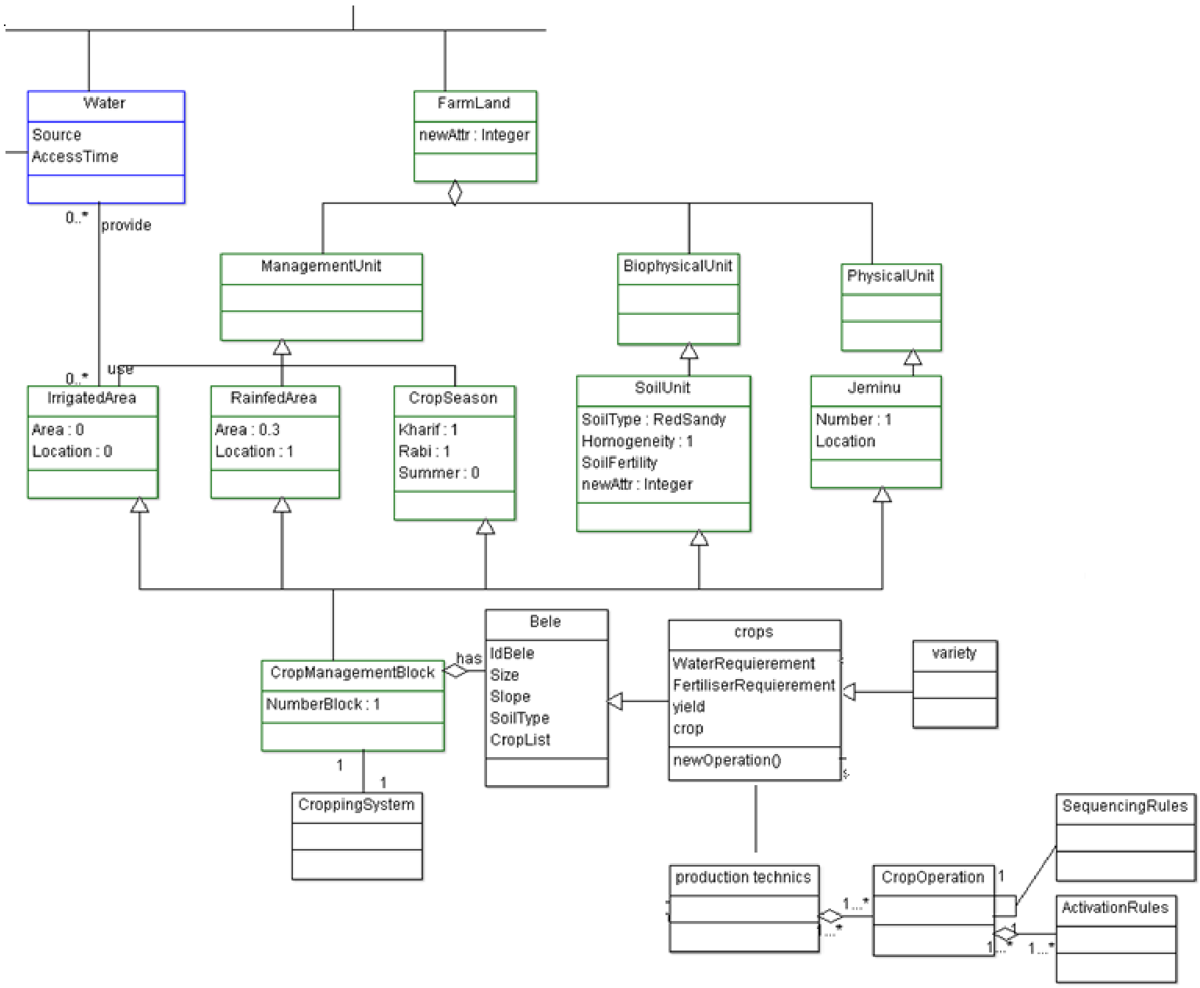


Figure Appendix 3. 5 Zoom on land organization.

Farmers use different equipements depending on the activity they realize (Figure Appendix 3.6). For instance, cultivation works are mainly done with a tractor and its implements, weeding, tilling, and levelling are often done with plough and animal traction or by hand, pesticide sprayers are used to treat pests and diseases, and irrigation requires specific equipement.

The farmer can owned his equipment or hire it (like for the labor, farmers that hire a tractor for cultivation will organize their field work depending on the other farmers' action).

Irrigation equipement can be fixed (drip) or movable (sprinkler) delimiting whether the irragable area is changing in time.

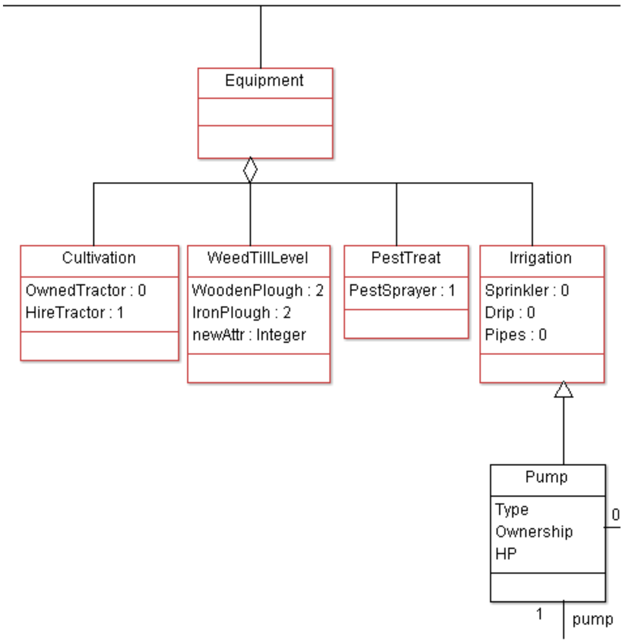


Figure Appendix 3. 6 Zoom on equipment management.

Owning animals is important for Indian farmers (Figure Appendix 3.7). First, an important part of the cultivation work is done by animal traction (bullocks or bulls that can be owned by the household or hired from the village). Second, animals are a source of food for the household providing milk and meat. Notice that the manure is also used to spray in the field as farm yard manure.

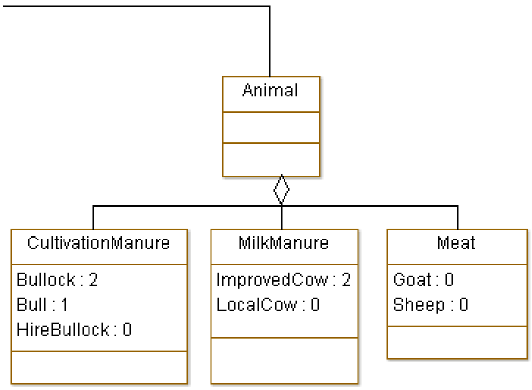


Figure Appendix 3. 7 Zoom on animal organization.

APPENDIX 4: ECONOMIC MODEL - MODEL EQUATIONS

Construction cost of borewells (Rs):

$$COST_{well} = (1 + 100 \times FAIL_{well}) \times (486.33 \times WELL_{depth} - 0.00824 \times WELL_{depth}^{2}).$$

Pump cost (Rs):

The pump cost $COST_{pump}$ depends on the pump's total horse power HP:

$$COST_{pump} = 3570 \times HP$$

Flow rate (m^3/h):

The flow rate (FR) is

$$FR = 79.93 \times {WT_{depth}}^{-0.728}$$

However, the existence of several borewells within a short distance of one another, as occurs among Indian farms, influences total flow rate; thus, maximum water abstraction capacity is not directly proportional to the number of borewells.

$$FR = (1 + 0.38 \times ((HP - 7) / 7)) \times 79.93 \times {WT_{depth}}^{-0.728}$$

The flow rate over a specific time-period (W) is considered the state variable of our dynamic model. The flow rate expected for the next time period (W') is stochastic because it considers borewell recharge ($RATE_{runoff}$) from expected rainfall ($rain_{S1}$ and $rain_{S2}$) and wear on the equipment ($RATE_{depreciation}$):

$W'_{S1} = pr_{S1} \times RATE_{depreciation} \times 79.93 \times (WT_{depth} - rain_{S1} \times RATE_{runoff})^{-0.728}$ and
$W'_{S2} = pr_{S2} \times RATE_{depreciation} \times 79.93 \times (WT_{depth} - rain_{S2} \times RATE_{runoff})^{-0.728}$

Depreciation rate:

Like any other capital asset of production, borewells and pumps wear out over time. The depreciation rate ($RATE_{depreciation}$) is estimated as 0.05.

Irrigation maintenance cost (Rs):

The irrigation maintenance cost $COST_{maintenance}$ is estimated as a function of the potential amount of water used $\overline{W}$:

$$COST_{maintenance} = 6598 \times \overline{W}^{0.16}$$

Electric power (kWh):

The electric power used for irrigation($POWER_{irrigation}$) is

$$POWER_{irrigation} = 745.7 \times HP$$

APPENDIX 5: ECONOMIC MODEL - YIELD ESTIMATIONS AND CLIMATIC EXPECTATIONS

1. Objective

The economic model uses yields to estimate the income from selling crops within the profit function depending on farmers' expectations on climate for the coming seasons. We aim at providing a yield matrix where yields depend on climate, irrigation and fertilization intensification. This matrix is an input to the economic model.

Five crops are used:
- Kharif: sunflower, marigold, sorghum, maize
- Rabi: maize
- Kharif and Rabi: turmeric

Six soils are used:

- soil11: loamy sand
- soil12: sandy loam
- soil13: gravely loamy sand
- soil14: sandy clay loam
- soil15: clay loam
- soil16: clay

2. Climatic expectations

Based on the five crops and the season and cropping duration of each crop type, we need to estimate total rainfalls in kharif (110-250 Julian days), rabi (240-400 Julian days) and for the year (kharif and rabi, 110-360 Julian days).

NB: time windows for the rainfalls are the minimum and maximum Julian days obtain from the STICS files that were calibrated and used by Avignon team and for the pump model calibration.

We used the climatic serial of Maddur enter in RECORD. Daily rainfalls are provided from 1973 to 2013. Kharif and rabi rainfalls are approximate by lognormal function (kharif: meanlog=6.181978, sdlog=0.2735082; rabi: meanlog=5.714544, sdlog=0.3949741) and the "year" is approximate by a normal function (mean=811.2707, sd=185.8911).

Years can be considered poor, below average, average, above average, good (Table Appendix 4.1).

Table Appendix 4. 1 List of year depending on rainfall types and season.

Kharif

poor	below average	average		above average	good
<600	600-730	730-870		700-1000	>1000
2002	1987	2000	1997	2010	1975
1976	1981	1985	1995	2007	
2003	2012	1989	1974	1992	
	2001	1982	1980	1993	
	2008	1983	2009	1991	
	1990	2006	1973	2011	
	1999	1998	1979	1978	
	1984	1996		1994	
	2005	1977		2013	
		1986			
		1988			
		2004			

Rabi

poor	below average	average		above average	good
<600	600-730	730-870		700-1000	>1000
1973	2001	1982	2013	1981	1977
	2002	1999	2006	1994	2005
	1983	1974	2011	2008	2000
	1989	1985	1975	1996	
	1990	1980	2004	1984	
	1998	1995	1978	2009	
	1988	1991	2010	1987	
	2003	1997	2007	1986	
		1976	1979		
		2012			
		1993			
		1992			

Kharif+Rabi

poor	below average	average		above average	good
<600	600-730	730-870		700-1000	>1000
2001	1973	1974	2004	1977	1975
2002	1976	1979	2006	1978	
2003	1981	1980	2007	1994	
	1982	1984	2008	2000	
	1983	1986	2009	2005	
	1985	1987	2010		
	1988	1991	2011		
	1989	1992	2013		
	1990	1993			
	1998	1995			
	1999	1996			
	2012	1997			

3. Yield expectations

Irrigation can be optimal, 75%, 50% 25% or none.

Based on experimental plots, we fixed irrigation dose to 15mm.

3.1. Optimal irrigation

Optimal irrigation is estimated by the automatic irrigation on STICS.

STICS automatically calculates water inputs so as to satisfy water requirements at the level of the RATIOL parameter (water stress index): the model triggers irrigation each time the stomatal stress index (SWFAC) is less than RATIOL. Irrigation amounts (AIRG) are then calculated so as to replenish the soil water reserve (HUR) to field capacity (HUCC) down to the rooting front (ZRAC) without exceeding the maximum dose authorized by the irrigation system (DOSIMX). Irrigation is applied only if AIRG > DOSEIRRIGMIN (the minimal dose allowed to do an irrigation). We force irrigation dose to be 15mm (DOSIMX = DOSEIRRIGMIN = 15). At the time of sowing, irrigation is provided if it has no rained, to enable germination. Irrigation at sowing is 15mm (IRRLEV) or less depending on soil water reserve.

STICS optimal irrigation provides the optimal number of irrigation and associated doses. The overall volume of water provided to the plant by irrigation is the sum of all irrigations during crop growth.

Since STICS is supposed to cover the plant water need, the yield function is expected to be uniform for all climates (see graphs below for soil11). The marigold is not uniform for soil 11, over 430mm of rainfall, it seems like the marigold yield is decreasing. Marigold is sensitive to water logging, in rainy season, well internal drainage is important. For the other crops, not having a uniform function can be explained by abundant rainfalls happening when the crop do not need much water.

3.2. Non-optimal irrigations: 75%, 50%, 25%

Each year, STICS optimal irrigation gave the number of irrigation and total irrigation volume V_{opt} provided to the plant. We can deduce non-optimal irrigations as:

$V_{75\%}$ = 0.75*V_{opt} and #irrigation = $V_{75\%}$ / 15mm

$V_{50\%}$ = 0.50*V_{opt} and #irrigation = $V_{50\%}$ / 15mm

$V_{25\%}$ = 0.25*V_{opt} and #irrigation = $V_{25\%}$ / 15mm

To estimate yields from non-optimal irrigations, we use a decision model coupled with STICS and a climate model. The decision model describes simple management practices with time of sowing and harvest fixed. Number of irrigation and fertilization doses depends on the intensification of the management practices. 108 management practices (ITK) are identified. Crossing with the 6 soils, 5 crops and 5 types of climate, we obtained 960 simulations to run with the simulator "decision/STICS/climate".

NB: Fertilization intensification was defined from the experimental plots. Analysis from the big survey should highlight other levels of intensification. Due to time consideration, we will keep the first levels of intensification for the thesis. (sorghum= no fertilization/fertilization ; maize, sunflower, marigold=1level of fertilization, turmeric=2levels of fertilization).

3.3. Results

Table Appendix 4. 2 Yield equation for the crops and rainfall regimens.

MAIZE RABI	
Poor	$Y = 0.4284 +0.00223*V-0.0000042*V^2$
Below average	$Y = 0.6091 +00145*V-0.0000041*V^2$
Average	$Y = 0.9595 +0.00161*V-0.0000077*V^2$
Above average	$Y = 1.0938 +0.00156*V-0.0000085*V^2$
good	$Y = 1.1769 +0.00160*V- 0.0000095*V^2$
MAIZE KHARIF	
Poor	$Y = 0.5584 +0.00228*V-0.00000547*V^2$
Below average	$Y = 0.5584 +0.00228*V-0.00000547*V^2$
Average	$Y = 0.6368 +0.00229*V-0.0000061*V^2$
Above average	$Y = 0.8461 +0.0021*V-0.0000094*V^2$
good	$Y = 0.9641 +0.00221*V-0.0000118*V^2$
SUNFLOWER	
Poor	$Y = 0.35691 +0.00426*V-0.0000198*V^2$
Below average	$Y = 0.35691 +0.00426*V-0.0000198*V^2$
Average	$Y = 0.4068 +0.0065*V-0.0000375*V^2$
Above average	$Y = 0.4068 +0.0065*V-0.0000375*V^2$
good	$Y = 0.4965 +0.0057*V-0.000040*V^2$
SORGHUM	
Poor	$Y = 0.4882$
Below average	$Y = 0.5752$
Average	$Y = 0.6429$
Above average	$Y = 0.7190$
good	$Y = 0.7692$
TURMERIC	
Poor	$Y = 0.133259 +0.004687*V-0.00000751*V^2$
Below average	$Y = 0.18425 +0.0055710*V-0.0000101*V^2$
Average	$Y = 0.214807 +0.006250*V-0.0000120*V^2$
Above average	$Y = 0.224425 +0.009054*V-0.0000195*V^2$
good	$Y = 0.240615 +0.01097*V-0.0000250*V^2$
MARIGOLD	
Poor	$Y = 1.8898 +0.01246*V-0.00005048*V^2$
Below average	$Y = 2.3424 +0.01129*V-0.00005644*V^2$
Average	$Y = 2.5974 +0.0106*V-0.000059*V^2$
Above average	$Y = 2.5974 +0.0106*V-0.000059*V^2$
good	$Y = 2.5974 +0.0106*V-0.000059*V^2$

APPENDIX 6: OPERATIONAL DECISION AND MODELING

The agent sub-system represents an activity plan that is the different technical operations to be performed and consists of a graph of tasks and relations between tasks. Formally, the activity plan is a direct multi-graph without loop (G=(V, E)), where V represents the tasks and E the links or relations between the tasks. The tasks are defined as tuples:

Preconditions represent the requirements for executing task. Preconditions are a set of predicate functions, each of which queries the knowledge base. An example can be: "Did it rain in the last three days?" This function returns TRUE or FALSE. If all predicates are TRUE, then the preconditions are valid.

Status describes the current phase of the task as one of the following: {WAITED, STARTED, ENDED, FINISHED, or FAILED}.

Time windows represent the earliest and latest starting and ending dates.

Links represent relations between two tasks. A link can be valid or invalid according to the status of the source and target tasks. Like tasks, links are defined as tuples:

– Types represent the relation between tasks i and j. A type can be one of the following: {SiSj,FiSj,FiFj}, indicating

whether one task must start (S) or finish(F) before the other.

– Time lag window defines the time lag in the relation between tasks, for example, ensuring that task j can start

after two units of time after the end of task i.

A crop management decision model is then defined by(i) a set of variable members of KB and associated facts (update functions); (ii) tasks and associated predicates, rules, and time windows; and (iii) temporal relations between tasks.

A knowledge base (KB) contains all information about the system that the farmer can use to reach a decision: dynamics of the state variables, state of the resources, and also spatial information about farm structure using geographic information system (GIS) (Dury 2011). Observations received by the decision model update the KB using functions called"facts."

1. Management operation description

Twelve activities are identified:

1- FYM

This activity describes the farmer applying farm yard manure to his field. Manure is applied before any land preparation work at the beginning of the cropping season, after the first rains. Farm yard manure application requests the load capacity of the soil good enough to allow the tractor to pass in the field. Dose is measured in *tractor load/ac* (will be convert into T/ha).

2- Tractor plough campaign

After applying farm yard manure, the farmer will start his land preparation. Most of the farmer who do not have a tractor will hire one. We suppose in our model that at least one tractor plough (and at max 3 tractor plough) is done. Tractor plough may be repeated several times depending on the soil structure and the cost of it. We suppose that farmer will repeat their tractor ploughing until they reach an optimal soil structure (to be determine in term of STICS variables (da(30cm) for instance) and optimal/acceptable threshold). In the decision model, tractor plough is described as a tractor ploughing campaign. The decision model inform the Operating System that the campaign has start and it is the Operating System that determine if ploughing should be done depending on soil structure. Tractor ploughing is done after rainfall when the load capacity is good and the soil humidity enough high for the plough to go deep enough.

3- Bullock plough campaign

If the soil structure need for the crop (deep roots or superficial roots) is not good enough, then farmers practice more land preparation by animal traction and wooden or iron plough. Once again we suppose that all farmers can do bullock ploughing with their own bullocks or by hiring some. Bullock ploughing may not be done if the soil structure is good enough for sowing. In the other case, farmers can pass up to 3 times the bullocks. In the decision model, tractor plough is described as a bullock ploughing campaign. The decision model inform the Operating System that the campaign has start and it is the Operating System that determine if ploughing should be done depending on soil structure. Animal ploughing is done after rainfall when the load capacity is good and the soil humidity enough high for the plough to go deep enough.

4- Sowing

Once the soil structure is reached for sowing, farmers prepare the furrows and the seed bed. Crop species and variety had been selected at the beginning of the season (in our model we suppose they use only one variety). Advices on plant-to-plant and row-to-row space are obtained from websites, as well as depth of the seedling. Surveys provide weight of seeds sown for 1 acre. To get the sowing density from surveys we need to know the weight of one seed so that we can deduce the number of plant per hectare. Or we can use the website recommendation to deduce the variable density *plants/ha*. Sowing is done when humidity is apparent in at least 6inch of soil. We need to translate this information into STICS variable, maybe with HUM for a soil layer of 15cm. Most of sowing has to be done in clement temperature. Some crops need several days without rain after sowing (e.g. beetroot). If the conditions for sowing are not met, then the farmer adapts and can change crop or fallow his land (dynamically load a new plan or fail the rest of the plan).

5- Sowing check point

Farmers check the sowing possibility. When the sowing could not be done in time because of unsatisfactory conditions, they will sow another crop.

6- Germination check point

Farmers check the crop germination. When the germination rate is lower than an optimal value, they may resow the same crop, remove and sow another crop or keep it like this. Germination is favorable when no stress is encountered the first month of plant growth. We consider the hydric and nitrogen stress.

7- 7- 8- Fertilization_N, Fertilization_P, Fertilization_K

Amount of fertilizer was provided in all 3 surveys (big surveys, 27 surveys and experimental plot surveys). From the name of the fertilizer we were able to deduce the N, P, K quantity applied on plots. Information on time and crop stage of application was only provided for rainfed experimental plots. We crossed this information with crop management practices advised on the web. We defined 3 levels of fertilization intensification based on nitrogen application: high fertilization, low fertilization, none (*value kgN/ha*). Nitrogen fertilization may be applied in 1, 2 or 3 times. Phosphate and potassium fertilization are depending on soil type. We suppose in our model that P and K fertilization is applied only once as basal application. Fertilization is done at specific crop stage and no rainfall for 2days after application is preferred in optimal conditions. The fertilization operation has a fixed number of applications for each crop. Thus it may be better to have an activity for each application (for example: fertilization at sowing, fertilization at 25 days)

8- Irrigation campaign

In surveys, irrigation was described as a number of irrigation given per crops and an interval between two irrigations. In case of rainfall in the coming days, irrigation is supposed to be cancelled for this time. Volume applied at irrigation is not clearly expressed by the farmers. It seems like when they have electricity, the electric pump activate and pump from the borewell until the electricity shut down. When they have a tank, they will pump and store water directly to the tank, then will irrigate from the tank. Two possibilities: 1- we suppose they pump water all time long they have electricity, 2- we fixed a soil humidity threshold for which they stop pumping even if they still have electricity. As the model is a 1 day time step, we do not care about the different electricity time shift happening during the day. Concerning tank storage, two possibilities: 1- farmers distribute all their water during the day (in this case the tank do not need to be modeled in the model), 2- water can be stored until the next irrigation period, the pumping is then reduce due to the water volume already available in the tank (in this case, we need to model the tank (evaporation, recharge with rain, and get information on size and storage capacity). A campaign of irrigation is initiated and the operating system starts the irrigation if the rainfall conditions, the interval and the number of time of application are respected.

9- 11- Pest treatment and weeding campaigns

Pest treatment and weeding is applied only when farmers estimate those pests and weeds are threatening their crops. In the surveys, pest and weed pressure are quantified as "no problem", "low", "medium", and "high". Pest and weed are not managed into the STICS model. A pest and weed model will be created to send a pressure value to the decision model. We will use a function modeling pest and weed pressure increasing with time and going back to zero when pesticide or weeding are done by the farmer. In the decision model, the activities will be pest and weed campaigns where several operations can be done. The decision model informs the Operating System that the campaign has started, and it is the Operating system that will decide when to act depending on the pressure rate provided by the pest and weed models.

10- Harvest

Farmers harvest their crops when it reaches an optimal stage of maturity. When the harvest is done over several days, then the farmer need to be sure that it won't rain. Some crops have sequential harvest (marigold, sunflower, cotton, beans, chili, tomato...), for STICS (simulate a crop plot at the same stage) we will consider that harvest is done only in one time for all crops.

2. Activities, rules, predicates and the decision plugin of RECORD

   We use the plugin decision within the RECORD platform. Before going to RECORD, we need to clearly express different part of the decision: activities, activity parameters, activity time windows, rules and predicates, activities precedence relations and effects (Bergez et al. 2016).

Activities and parameters

Activities have time-windows (start date – end date)

Table Appendix 5. 1 Description of activities and parameters used.

Activity	Type	Effect Parameters
FYM	fertilization	Dose(T/ha)
Tractor Plough campaign	Land preparation	Depth(cm) *Min passing** *Max passing**
Bullock Plough campaign		
Sowing	sowing	Density (plant/m2)
Sowing Check	check	*Fail plan, load plan***
Germination Check	check	*Fail plan, load plan***
Fertilization-N	fertilization	Dose(kg/ha)
Fertilization-P		
Fertilization-K		
Irrigation campaign	irrigation	*Number of irrigation** *Interval**
Pest treatment campaign	Pest treatment	*Re-initialize pest function to 0***
Weeding campaign	Weeding	
Harvest	harvest	

*parameters used by the operating system

**dynamic effect

Predicates and Rules

Table Appendix 5. 2 Description of predicates used in rules.

Predicates	Description	Model dynamic	Variables	sign
CropStageMin	Minimum crop stage	STICS	BBCH	>
CropStageMax	Maximum crop stage	STICS	BBCH	<
LoadCapacity	Ground load capacity	STICS	HUR/HUCC	<=
SoilHumidity	Soil humidity on sowing horizon (15cm)	STICS	HUR/HUCC	>
Densite	Average (Min (TURFAC, INNLAI)) for 10 last days	STICS	Average (Min(TURFAC;INNLAI))	>=
PredictedRainfall	Sum of the rainfall of day j, j+1, j+2	CLIMATE	Rain(j)+rain(j+1)+rain(j+2)	<
MinPast Rainfall	Sum of the rainfall of day j-1 to j-10	CLIMATE	Rain(j)+rain(j+1)+rain(j+2)+ Rain(j+3)+rain(j+4)+rain(j+5)+ Rain(j+6)+rain(j+7)+rain(j+8)+ Rain(j+9)+rain(j+10)	>=
PastRainfall	Sum of the rainfall of day j-1, j-2, j-3	CLIMATE	Rain(j-1)+rain(j-2)+rain(j-3)	<
PestPressure	Pest pressure	PEST	Ppest	>
ClementTemperature	Clement temperature	CLIMATE	Tmax	>
Deadline	Force activity at the end of the time-window	CLIMATE	date	>

Optimal rules: rules for optimal conditions

Relaxed rules: rules for acceptable conditions (relaxed predicate thresholds).

Table Appendix 5. 3 Description of rules used by activities.

Activity	Rules	Predicates
FYM	Optimal/acceptable rule	Load capacity PastRainfall
	Deadline rule	Deadline
Tractor Plough campaign	Optimal/acceptable rule	Load capacity SoilHumidity
	Deadline rule	Deadline
Bullock Plough campaign	Optimal/acceptable rule	Load capacity SoilHumidity
	Deadline rule	Deadline
Sowing	Optimal/acceptable rule	Load capacity SoilHumidity MinPastRainfall PredictedRainfall ClementTemperature
	Deadline rule	Deadline
Germination Check	Optimal/acceptable rule	CropStageMin CropStageMax densite
	Deadline rule	Deadline
Fertilization-N	Optimal/acceptable rule	CropStageMin CropStageMax PredictedRainfall
	Deadline rule	Deadline
Fertilization-P	Optimal/acceptable rule	CropStageMin CropStageMax PredictedRainfall
	Deadline rule	Deadline
Fertilization-K	Optimal/acceptable rule	CropStageMin CropStageMax PredictedRainfall
	Deadline rule	Deadline
Irrigation campaign	Optimal/acceptable rule	CropStageMin CropStageMax PredictedRainfall PastRainfall
	Deadline rule	Deadline
Pest treatment campaign	Optimal/acceptable rule	PredictedRainfall PestPressure
	Deadline rule	Deadline
Weeding campaign	Optimal/acceptable rule	CropStageMin CropStageMax PredictedRainfall
	Deadline rule	Deadline
Harvest	Optimal/acceptable rule	CropStageMin CropStageMax PredictedRainfall
	Deadline rule	Deadline

Relationship between activities

Precedence relationship between activities can be established with rules: FS (Finish-Start), SS (Start-Start), FF (Finish-Finish) and a time lapse (minimum and/or maximum time between activities).

Table Appendix 5. 4 Precedence constraints between activities

Activity	Previous activity
FYM	Previous crop harvested
Tractor Plough campaign	FYM
Bullock Plough campaign	Tractor Plough
Sowing	Tractor Plough or Bullock Plough
Sowing Check	Sowing
Germination Check	Sowing Check
Fertilization-N	Sowing Check
Fertilization-P	Sowing Check
Fertilization-K	Sowing Check
Irrigation campaign	Sowing Check
Pest treatment campaign	Sowing Check
Weeding campaign	Sowing Check
Harvest	Germination Check

3. Example for Turmeric:

Table Appendix 5. 5 Predicates and threshold values used for the turmeric.

ACTIVITY	INITIAL PREDICATES	MODEL PREDICATES
FYM	"after the first rains of the monsoon"	PastRainfall>1mm
	"pass with the tractor"	LoadCapacity<=1.2
Tractor plough Campaign	"pass with the tractor"	LoadCapacity<=1.2
	"enough soil humidity to plough"	SoilHumidity>0.9
Bullock plough Campaign	"pass with the tractor"	LoadCapacity<=1.2
	"enough soil humidity to plough"	SoilHumidity>0.9
Planting	"at least 6inch humidity"	SoilHumidity>0.6
	"rained last past days"	MinPastRainfall<=30mm
	"rained last past days"	PastRainfall>1mm
	"sow at good temperature"	ClementTempenrature>12
Germination check	"average stress over the 10 last days”	densite>=0.5
Fertilization_N	" rain for coming 2days"	PredictedRaindall>1mm
Fertilization_P	" rain for coming 2days"	PredictedRaindall>1mm
Fertilization_K	" rain for coming 2days"	PredictedRaindall>1mm
Irrigation Campaign	"did not rain much last days"	MinPastRainfall<50
	"won’t rain much next days"	PredictedRainfall<1mm
pest treat campaign	"treat when pest”	PestPressure=1
Weed treat campaign	"after a good rain"	PastRainfall=rain(j-1)+rain(j-2)>30mm
harvest	"when crop is mature"	CropStageMax=BBCH<97
	"when crop is mature"	CropStageMin=BBCH>85
	"no rain during harvest"	PredictedRaindall<1mm

APPENDIX 7: COUPLED MODEL – A VILLAGE WITH TWO FARMS

The experiment model simulates a virtual village composed of two virtual farms (F1 and F2) both having access to ground water on the same AMBHAS cell. Both farms have two plots (F1P1, F1P2 and F2P1, F2P2) of variable size (size_F1P1, size_F1P2 and size_F2P1, size_F2P2) from year to year. The first farmer operates one hectare land (size_F1P1 + size_F1P2) and has 1 bullock to cultivate; the second has two heactares of land (size_F2P1 + size_F2P2) to cultivate and two bullocks. None of them has tractor. The farmer and his wife are both working on the farm for both farms. Both farms can hire labor and rent equipment from the village (110 female labor, 90 male labor, 4 bullocks, 1 tractor). A borewell can be drilled on each plot and is defined by its HP and well depth (HP_F1P1, HP_F1P2, HP_F2P1, HP_F2P2, Well_Depth_F1P1, Well_Depth_F1P2, Well_Depth_F2P1, and Well_Depth_F2P2).

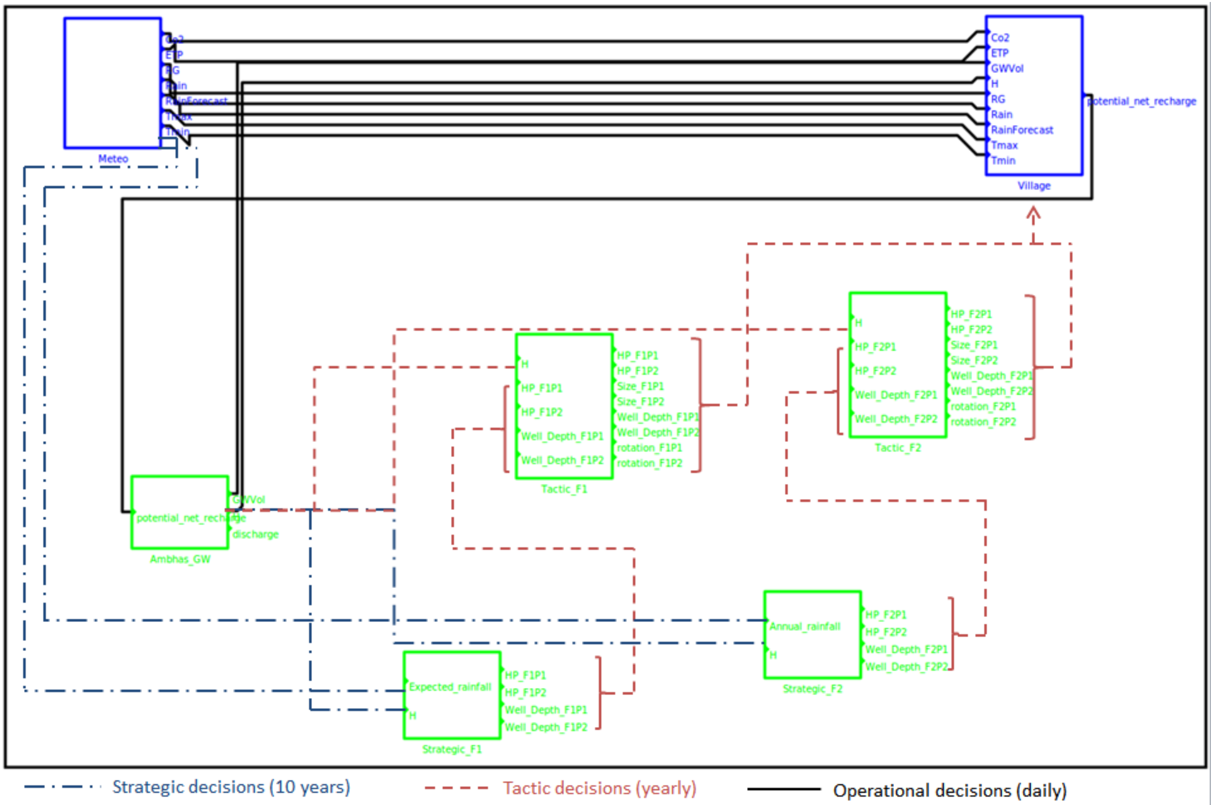


Figure Appendix 6. 1 : NAMASTE top model – Strategic_F1, Strategic_F2 are the strategic decision models; Tactic_F1 and Tactic_F2 are the tactic decision models; Village include the operational decision models.

The three levels of decision are simulated in the model. The strategic (Strategic_F1 and Strategic_F2) and tactic (Tactic_F1 and Tactic_F2) decisions are independent dynamic stochastic models from the economic approach presented in chapter 6. The operational decisions are represented by the Village sub-model (Figure Appendix 6.1). Strategic and tactic models are coded in C, other models are integrated within the RECORD platform. The coupling was done in C. An improvement will be to wrap up the economic models within the RECORD platform.

First, the strategic models run over 10 years of planning horizon. From the initial groundwater level obtained from the AMBHAS model and the expectations on climate obtained by the Meteo model, the strategic models decide the best investment in irrigation (HP and well_Depth).

Then, strategic decisions are sent to the tactic model that will reviews the cropping system (rotation and Size) depending on updated information and knowledge on climate (annual_rainfall) and groundwater level (H).

Finally, the cropping system (rotation and size) data are sent to the village model that updates parameters of wells and crops before running daily simulations.

In this appendix, we mainly detail the Village model used for the daily simulations at the operational level (Figure Appendix 6.2).

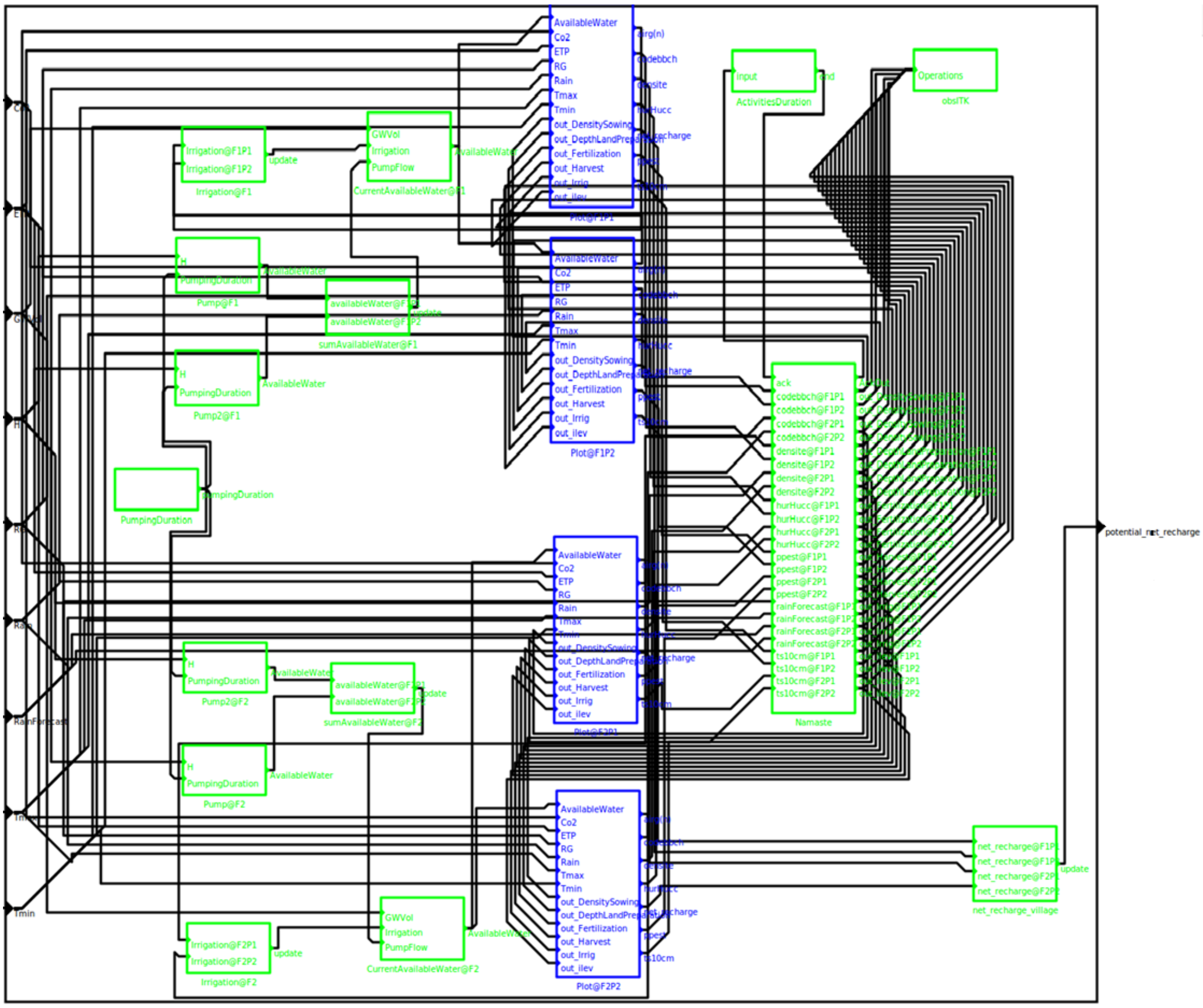


Figure Appendix 6. 2 : the Village model used for the daily simulations at the operational level. Boxes describe sub-models, lines are connections between models.

The Village model is made of three main parts: 1) hydrological part to estimate the available water for irrigation; 2) decisional part with daily technical operations; 3) biophysical part from operation execution to crop growth and water flows in the soil.

1) Hydrological part

The hydrological part is made of five types of sub-models to get available water for irrigation per plot from the groundwater (Figure Appendix 6.3).

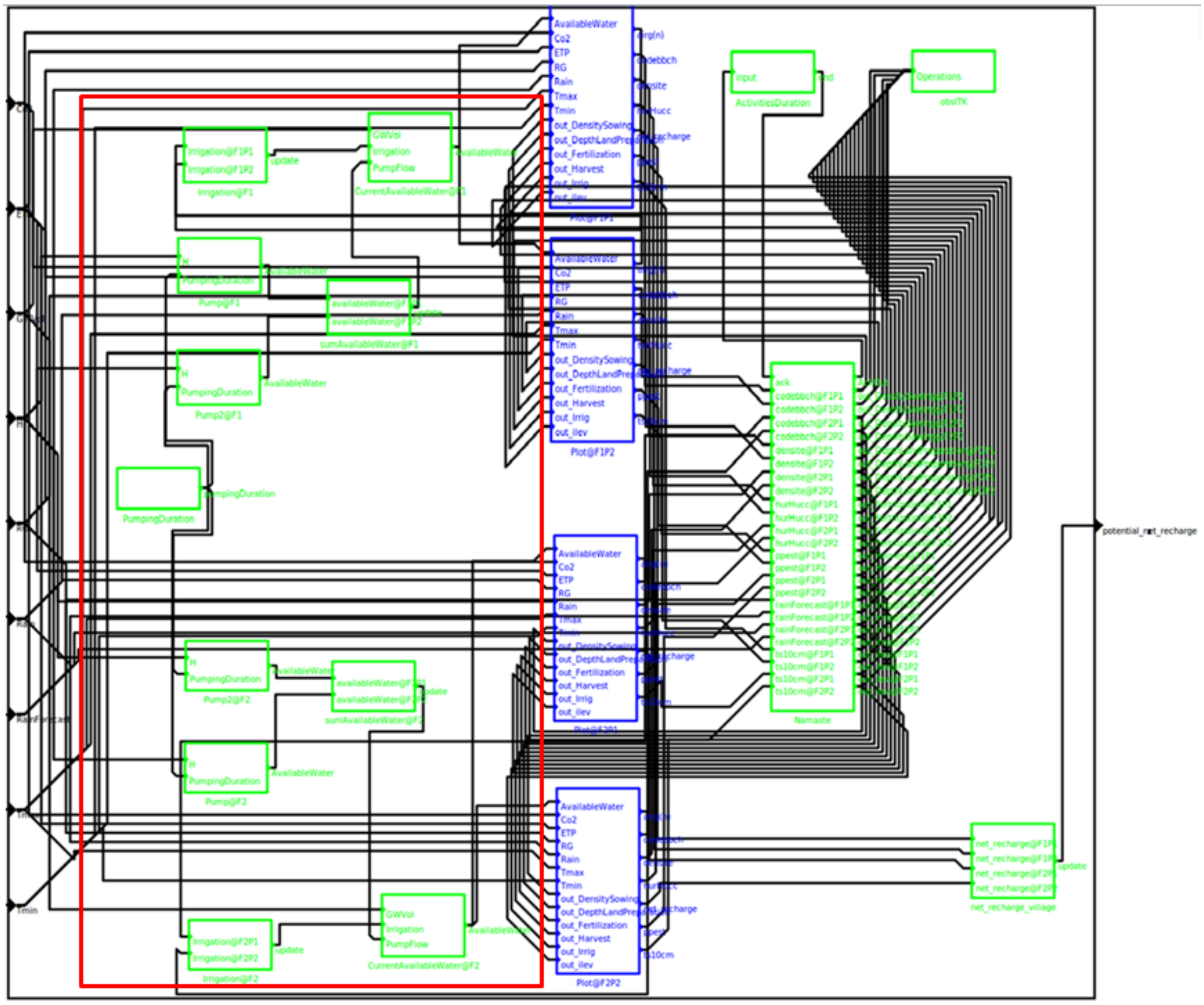


Figure Appendix 6. 3 : The Village model – details on the hydrological parts made of fives types of sub-models to get available water for irrigation per plot from the groundwater.

- PumpingDuration

The PumpingDuration sub-model provides the number of hours of electricity available for pumping. Hours in kharif and rabi are entered in the parameters of the model so that it may be changed for scenario purpose.

Table Appendix 6. 1 : Description of inputs, outputs, parameters and equations used in the PumpingDuration sub-model.

Inputs		**Parameters**	**Outputs**	
		PumpingDurationK = 4 (hours of electricity in kharif)	PumpingDuration	Hours of electricity available for pumping
		PumpingDurationR = 3 (hours of electricity in rabi)		
Equation				

- Pump@F1, Pump2@F1, Pump@F2,Pump2@F2

Four pump models estimate the maximum amount of water a single pump can extract from groundwater each day. Based on the groundwater level provided by AMBHAS and the pumping duration provided by the PumpingDuration model, it estimates the available water obtained by operating the pump. First it converts the groundwater level into water table depth from the ground. Then it calculates the pump flow based on the empirical relationship between groundwater and borewell yield established in Berambadi watershed (Figure Appendix 6.4).

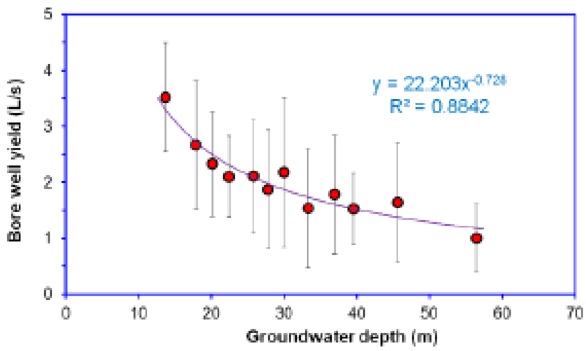


Figure Appendix 6. 4 : Borewell yield (pump flow) in the Berambadi watershed.

The units for the borewell yield in the empirical relationship are in L/s but in the pump model they are converted in m^3/h. So the first coefficient is multiplied by a conversion factor of 3.6 (3600/1000) so that the pump flow is $PumpFlow = 79.9308 \times WaterTableDepth^{-0.728}$.

Interference between borewells is considered with CoeffC so that when two borewells are on less than 2 hectares, the total available water is 1.3 the pump flow instead of 2 when there is no interference between borewells.

Table Appendix 6. 2 : Description of inputs, outputs, parameters and equations used in the Pump sub-models.

Inputs		**Parameters**	**Outputs**	
H	Groundwater level from AMBHAS (in meter above sea level)	Altitude = 700m	AvailableWater	Available water for irrigation (m3/day)
PumpingDuration	Hours of pumping from PumpingDuration model	CoeffA = 79.9308		
		CoeffB = -0.728		
		CoeffC = 1 if first borewell, 0.3 if second borewell due to interference effects between wells.		
		WellDepth = Well_Depth from Tactic Model		
Equation				
WaterTableDepth = max(0.0, Altitude - H(-1)); If WaterTableDepth() > WellDepth { PumpFlow = 0 }; else { PumpFlow = max(0.0, CoeffA * WaterTableDepth() ^{CoeffB} ; } AvailableWater = max(0.0, PumpFlow() * PumpingDuration() * mCoeffC);				

- SumAvailableWater@F1, SumAvailableWater@F2

SumAvailableWater sub-models sum the available water provided by the two pumps on the farm.

Table Appendix 6. 3 : Description of inputs, outputs, parameters and equations used in the SumAvailableWater sub-models.

Inputs		**Parameters**	**Outputs**	
AvailableWater@P1	Available water from pump 1 (m3/day)		update	Total available water for the farm (m3/day)
AvailableWater@P2	Available water from pump 2 (m3/day)			
Equation				
Update = AvailableWater@P1 + AvailableWater@P2				

- Irrigation@F1, Irrigation@F2

The Irrigation sub-models sum the water demanded for irrigation from the STICS models. It is used in the hydrological part to determine when irrigation occurs.

Table Appendix 6. 4 : Description of inputs, outputs, parameters and equations used in the Irrigation sub-models.

Inputs		**Parameters**	**Outputs**	
Irrigation@F1P1 or Irrigation@F2P1	Airg(n) from SticsOut (water needed for irrigation) (L/m²/day)		update	Total water needed for irrigation (L/m²/day)
Irrigation@F1P2 or Irrigation@F2P2	Airg(n) from SticsOut (water needed for irrigation) (L/m²/day)			
Equation				
Update = Irrigation@F1P1 + Irrigation@F1P2 or Update = Irrigation@F2P1 + Irrigation@F2P2				

- CurrentAvailableWater@F1, CurrentAvailableWater@F2

CurrentAvailableWater sub-models determine the total available water for irrigation. We consider the water can be stocked for n days before being used for irrigation. This hypothesis is used to cover the observation that farmers are irrigated every day a part of their field but do not have enough water to irrigate the entire plot in one day. When irrigation occurs the water stock is reinitiated to zero. The available water is the minimum between the summations of the amount of water extract during n days and the ground water volume (AMBHAS). This water amount is distributed equally between plots. An improvement may be to attribute the quantity of water available depending on the water demand by each plot.

Table Appendix 6. 5 : Description of inputs, outputs, parameters and equations used in the CurrentAvailableWater sub-models.

Inputs		**Parameters**	**Outputs**	
GWVol	Groudwater volume from AMBHAS (m3/day)	n = 10 (number of days that water is stocked for the future irrigation)	AvailableWater	Available water for irrigation for each plots (m3)
Irrigation	Update from Irrigation model (L/m²/day)			
PumpFlow	Update from SumAvailableWater (m3/day)			
Equation				
if (Irrigation(-1) > 0) { Water = 0 ; } Water = PumpFlow(); AvailableWater = $\sum_n Water$ AvailableWater = min(AvailableWater, GWVol(-1)); AvailableWater = AvailableWater/2.;				

2) Decisional part

The decisional part is made of three types of sub-models to get technical activities (Figure Appendix 6.5).

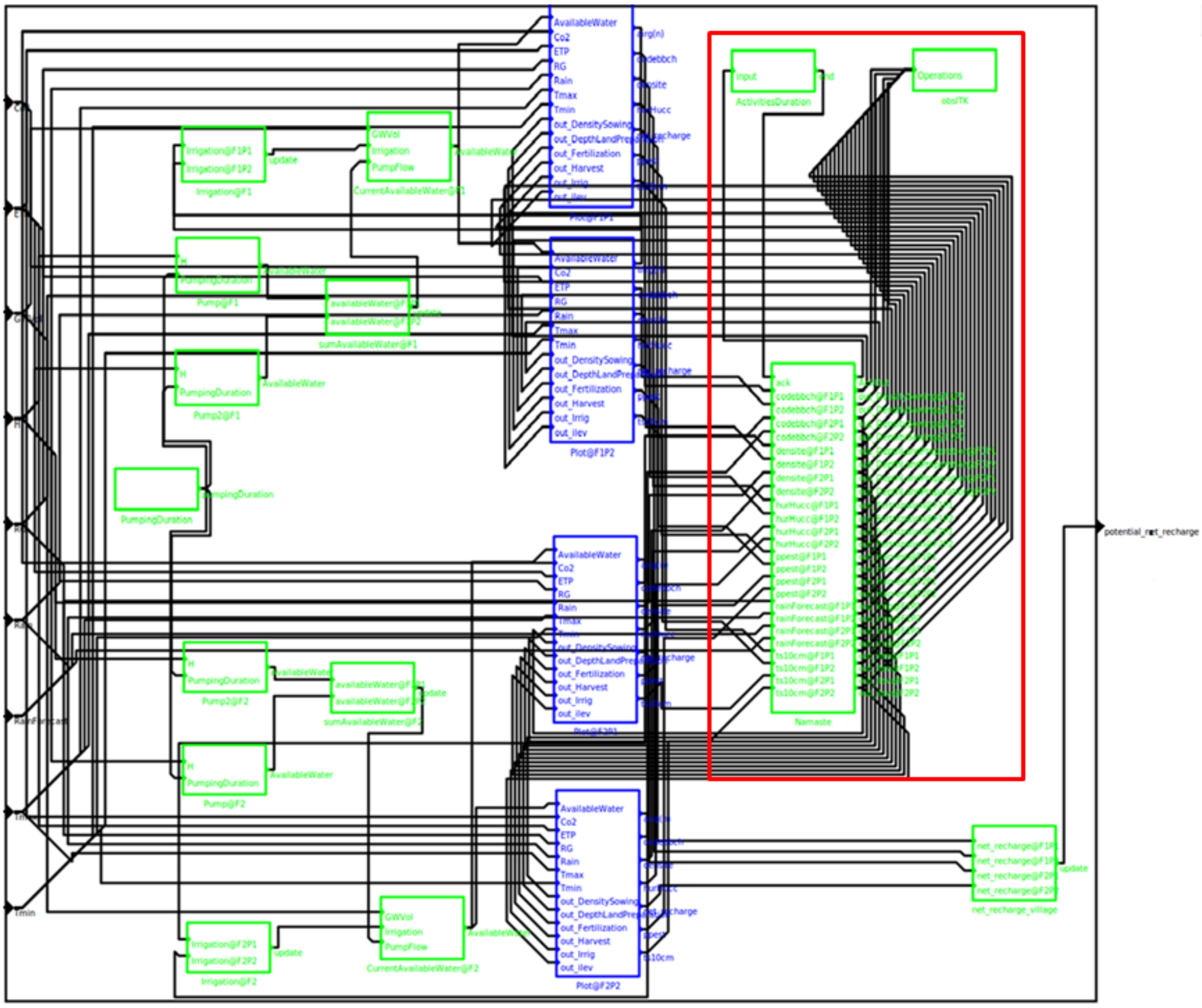


Figure Appendix 6. 5 : The Village model – details on the decisional part made of three types of sub-models to get technical activities

- ObsITK

It is a very simple model to observe all operations done one day. The state of the model is a simple string. In this string all the events (operations) of the day are concatenated. This model is util, and convenient to observe this aspect of the system.

- ActivitiesDuration

ActivitiesDuration sub-model manages duration of activities based on the parameter “duration” in the Namaste model. It receives the AckOut function from the Namaste model that informs the beginning of a technical activity and it sends a “end” message to the Namaste model once the activity is supposed to be finished. If no duration is indicated in Namaste, the duration is considered to be one day. An improvement to this model may be to allow different durations for the different activities.

Table Appendix 6. 6 : Description of inputs, outputs, parameters and equations used in the ActivitiesDurationr sub-model.

Inputs		**Parameters**	**Outputs**	
input	AckOut from Namaste model		end	Signal the end of the activity
Equation				

if (parameter ("duration") exists in Namaste) {
duration = get("duration"));
} else {
duration = 1.0; }				

- Namaste

The Namaste model manages the operational decisions of the farmer. It receives information from the SticsOut, ppest and the meteo models for the rules. It returns sowing, soil preparation, nitrogen fertilization and irrigation characteristics to be applied in SticsOut model. The crop management plan used to replace initial plan when sowing or germination failed is entered in the parameters of the model. The rotations and its durations and the plot sizes for each plots are provided by the Tactic models.

Table Appendix 6. 7 : Description of inputs, outputs, parameters and equations used in the Namaste sub-model.

Inputs		**Parameters**	**Outputs**	
Ack	End from activitiesDuration model	PlanReplace_Kharif_F1 = Plan MK_replace	AckOut	Acknowledgment of activity start
codebbch@F1P1	Bbch code from SticsOut model F1P1	PlanReplace_Kharif_F2 = Plan MK_replace	Out_DensitySowing @F1P1	Sowing density F1P1 (grains/m²)
codebbch@F1P2	Bbch code from SticsOut model F1P2	Rotation (FIP1 ; F1P2 ; F2P1 ; F2P2) = rotation from Tactic_F1 and Tactic_F2 models	Out_DensitySowing @F1P2	Sowing density F1P2 (grains/m²)
codebbch@F2P1	Bbch code from SticsOut model F2P1	Duration = 1	Out_DensitySowing @F2P1	Sowing density F2P1 (grains/m²)
codebbch@F2P2	Bbch code from SticsOut model F2P2	surfaceF1P1 = size_F1P1 from tactic_F1 model	Out_DensitySowing @F2P2	Sowing density F2P2 (grains/m²)
densite@F1P1	Average from moyen_densite model F1P1	surfaceF1P2 = size_F1P2 from tactic_F1 model	Out_DepthLandPreparation@F1P1	Tillage depth F1P1 (cm)
densite@F1P2	Average from moyen_densite model F1P2	surfaceF2P1 = size_F2P1 from tactic_F2 model	Out_DepthLandPreparation@F1P2	Tillage depth F1P2 (cm)
densite@F2P1	Average from moyen_densite	surfaceF2P2= size_F2P2 from	Out_DepthLandPreparation@F2P1	Tillage depth F2P1 (cm)

	model F2P1	tactic_F2 model		
densite@F2P2	Average from moyen_densite model F2P2		Out_DepthLandPreparation@F2P2	Tillage depth F2P2 (cm)
hurHucc@F1P1	hurHucc code from SticsOut model F1P1		Out_Fertilization@F1P1	Nitrogen dose F1P1 (kg/ha)
hurHucc@F1P2	hurHucc code from SticsOut model F1P2		Out_Fertilization@F1P2	Nitrogen dose F1P2 (kg/ha)
hurHucc@F2P1	hurHucc code from SticsOut model F2P1		Out_Fertilization@F2P1	Nitrogen dose F2P1 (kg/ha)
hurHucc@F2P2	hurHucc code from SticsOut model F2P2		Out_Fertilization@F2P2	Nitrogen dose F2P2 (kg/ha)
ppest@F1P1	Update from ppest model F1P1		Out_Harvest@F1P1	Harvest in F1P1
ppest@F1P2	Update from ppest model F1P2		Out_Harvest@F1P2	Harvest in F1P2
ppest@F2P1	Update from ppest model F2P1		Out_Harvest@F2P1	Harvest in F2P1
ppest@F2P2	Update from ppest model F2P2		Out_Harvest@F2P2	Harvest in F2P2
rainForecast@F1P1	rainForecast from Meteo model		Out_Irrig@F1P1	Irriagtion dose F1P1 (mm)
rainForecast@F1P2	rainForecast from Meteo model		Out_Irrig@F1P2	Irriagtion dose F1P2 (mm)
rainForecast@F2P1	rainForecast from Meteo model		Out_Irrig@F2P1	Irriagtion dose F2P1 (mm)
rainForecast@F2P2	rainForecast from Meteo model		Out_Irrig@F2P2	Irriagtion dose F2P2 (mm)
Ts10cm@F1P1	TS(1) from SticsOut model F1P1		Out_ilev@F1P1	day of the emergence stage F1P1
Ts10cm@F1P2	TS(1) from SticsOut model F1P2		Out_ilev@F1P2	day of the emergence stage F1P2
Ts10cm@F2P1	TS(1) from SticsOut model F2P1		Out_ilev@F2P1	day of the emergence stage F2P1
Ts10cm@F2P2	TS(1) from SticsOut model F2P2		Out_ilev@F2P2	day of the emergence stage F2P2
Equation				
RECORD decision plugin (see appendix 5)				

3) Biophysical part

The biophysical part is made of five types of models that execute technical operations and translate them into crop growth parameter and hydrological flux into the soil (Figure Appendix 6.6 and 6.7).

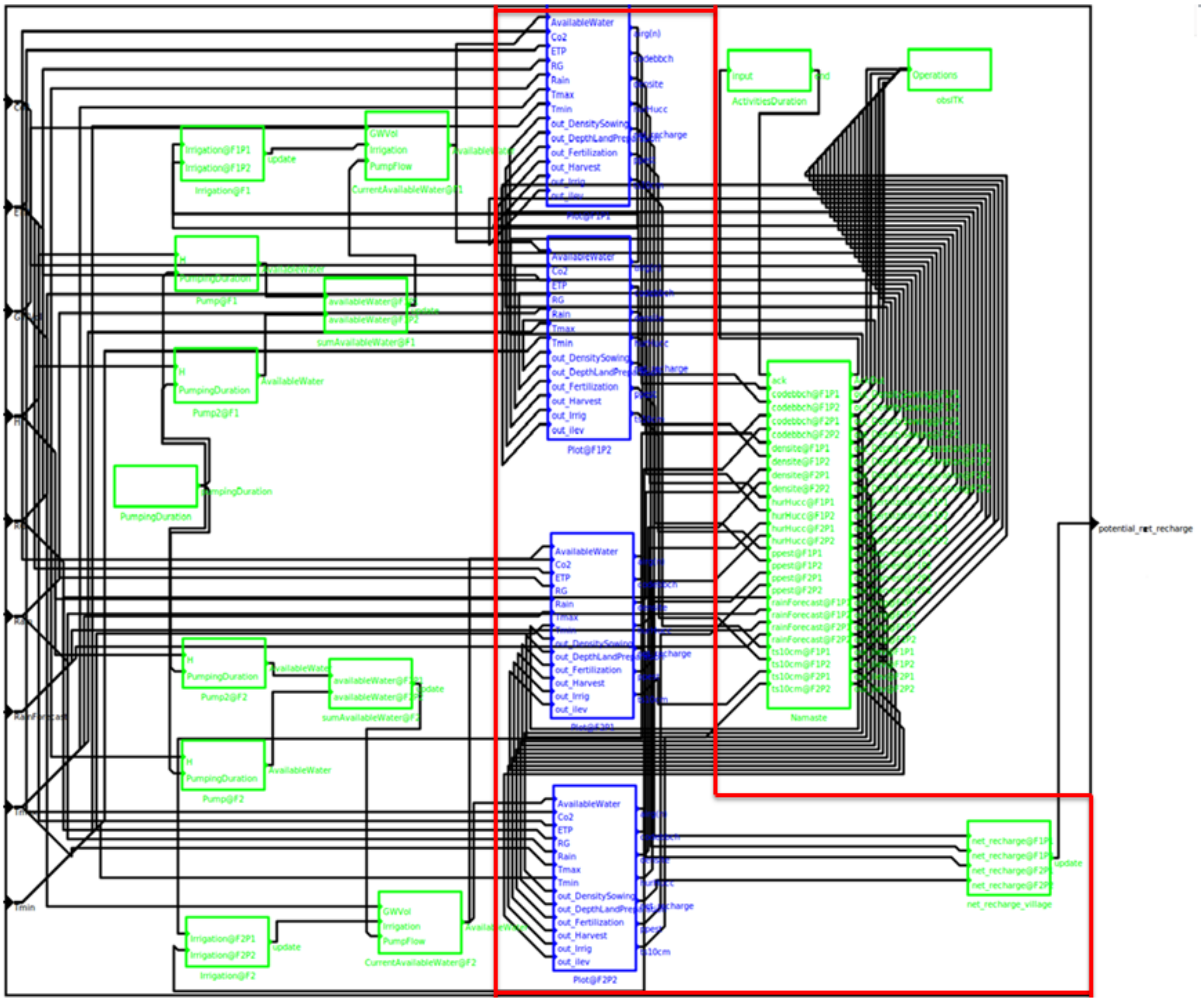


Figure Appendix 6. 6: The Village model – details on the biophysical part made of five types of models that execute technical operations and translate them into crop growth parameter and hydrological flux into the soil.

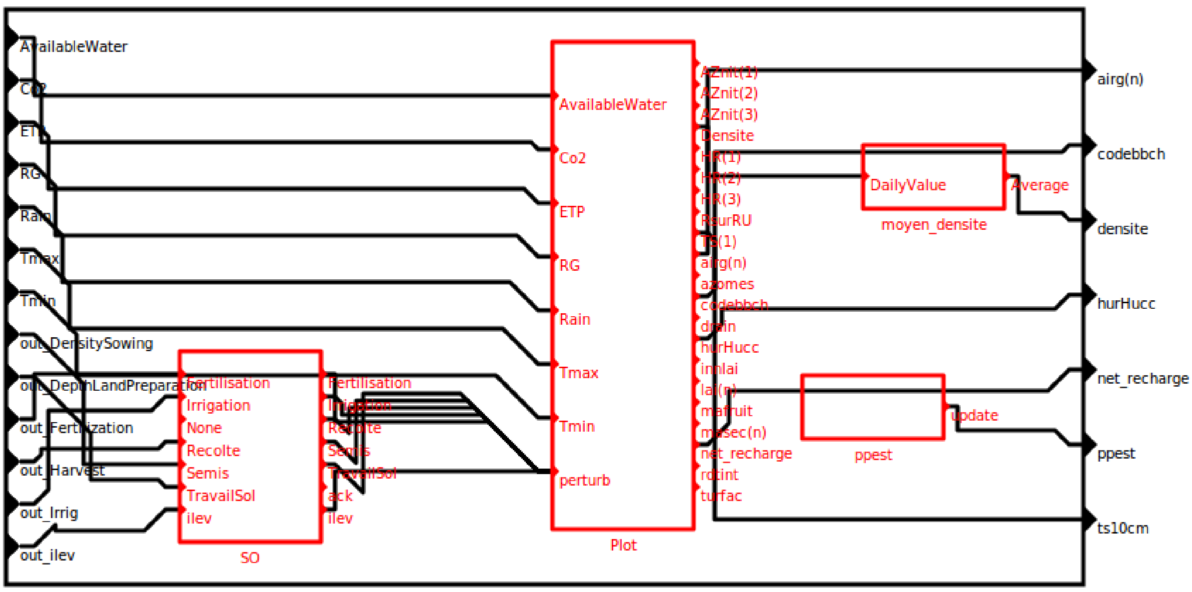


Figure Appendix 6. 7 : Details of the Plot model made of four sub-models.

- SO

The operating system SO model translates the decision orders from the Namaste model into action execution for the STICS model.

Table Appendix 6. 8 : Description of inputs, outputs, parameters and equations used in the SO sub-model.

Inputs		**Parameters**	**Outputs**	
Fertilization	Out_Fertilization from Namaste (kg/ha)		Fertilization	Nitrogen dose (kg/ha)
Irrigation	Out_Irrig from Namaste (mm)		Irrigation	Irriagtion dose (mm)
Recolte	Out_Harvest from Namaste		Recolte	Harvest (remove crop and load next USM)
Semis	Out_DensitySowing from Namaste (grains/m²)		Semis	Sowing density (grains/m²)
TravailSol	Out_DepthLandPreparation from Namaste (cm)		TravailSol	Tillage depth (cm)
ilev	Out_ilev from Namaste		ilev	day of the emergence stage
Equation				
Semis = semis * 1000				

- Moyen_densite

Table Appendix 6. 9 : Description of inputs, outputs, parameters and equations used in the Moyen_densite sub-model.

Inputs		**Parameters**	**Outputs**	
DailyValue	Densite from SticsOut model	n = 10	Average	Mean value of densite
Equation				
Average = mean (DailyValue (j) to DailyValue (j-n))				

- Ppest

This model is supposed to simulate pest attacks. It was not used during the thesis. An improvement will be to simulate pest attack as a random events sending 1 when there is an attack, 0 otherwise.

Table Appendix 6. 10: Description of inputs, outputs, parameters and equations used in the Ppest sub-model.

Inputs		**Parameters**	**Outputs**	
			update	Pest attack
Equation				
0				

- Plot

Plot sub-model is made of two parts: the rotator and STICS (Figure Appendix 6.8).

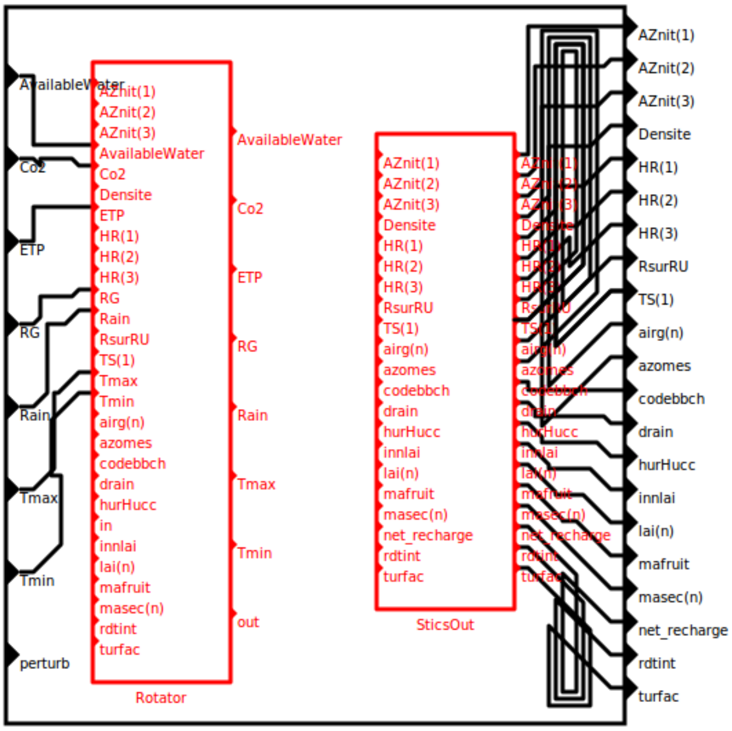


Figure Appendix 6. 8: Details of the Plot sub-model model made of two sub-models – the rotator and STICS.

The rotator allows simulating several crops one after another. Each crop is simulated by a STICS model that uses the final state of the previous USM as initial state. Rotations and plot size (converted from ha to m²) are entered as parameter and are from the Tactic model.

The SticsOut model simulates crop growth and hydrological flux in the soil.

Table Appendix 6. 11: Description of inputs, outputs, parameters and equations used in the Plot sub-models.

Inputs		**Parameters**	**Outputs**	
AvailableWater	Available water for irrigation from CurrentAvailableWater model (m3/day to be converted into mm/ha/day)		AZnit(1)	amount of NO3-N in the soil horizon 1 (kg.ha-1)
CO2	Carbon dioxide from the meteo model		AZnit(2)	amount of NO3-N in the soil horizon 2 (kg.ha-1)
ETP	Potential evaporation from the meteo model		AZnit(3)	amount of NO3-N in the soil horizon 3 (kg.ha-1)
RG	Radiation from the meteo model		Densite	daily stress (0-1)
Rain	Rainfall from the meteo model		HR(1)	water content of the soil horizon 1

				(% dry weight)
Tmax	Maximum temperature from the meteo model		HR(2)	water content of the soil horizon 2 (% dry weight)
Tmin	Minimum temperature from the meteo model		HR(3)	water content of the soil horizon 3 (% dry weight)
			RsurRU	Fraction of available water reserve (R/RU) over the entire profile (0-1)
			TS(1)	mean soil temperature (in horizon 1) (degreeC)
			Airg(n)	daily amount of irrigation water (mm/day)
			azomes	amount of NO3-N in soil over the depth "profmes" (kg/ha)
			codebbch	Bbch code
			drain	daily amount of water drained at the base of the soil profile (mm/day)
			hurHucc	Soil water reserve compared to filed capacity (%)
			Innlai	reduction factor on leaf growth due to nitrogen deficiency (0-1)
			Lai(n)	leaf area index (m^2/m^2)
			Mafruit	biomass of harvested organs (T/ha)
			Masec(n)	biomass of aboveground plant (T/ha)
			NetRecharge	Net recharge (m3/day)
			Rdtint	biomass of harvested organs (T/ha)
			turfac	turgescence water stress index (0-1)

Equation
PlotArea = Size * 10000 ; // convert from ha to m²

```
AvailableWater = AvailableWater * 1000; // convert from m3/day to mm/m²/day
AvailableWater = AvailableWater / PlotArea; // convert from mm/m²/day to mm/day
Airg(n) = min (AvailableWater ; irrigation);
hurHucc = hur / hucc;
densite = min (TURFAC ; INNLAI);
net_recharge= (drain – airg(n)) * PlotArea ; // convert from mm/day to mm/m²/day
net_recharge= net_recharge / 1000 ; // convert from mm/m²/day to m3/day
```

- Net_recharge_village

The net_recharge_village model cumulates the net_recharge from the different plots to return a global recharge to AMBHAS.

Table Appendix 6. 12 : Description of inputs, outputs, parameters and equations used in theNet_recharge_village sub-models.

Inputs		**Parameters**	**Outputs**	
Net_recharge@F1P1	Net recharge F1P1 (m3/day)		Net_recharge_village	Net recharge total (m3/day)
Net_recharge@F1P2	Net recharge F1P2 (m3/day)			
Net_recharge@F2P1	Net recharge F2P1 (m3/day)			
Net_recharge@F2P2	Net recharge F2P2 (m3/day)			
Equation				
Net_recharge_village = Net_recharge@F1P1+Net_recharge@F1P2+Net_recharge@F2P1+ Net_recharge@F2P2				

4) AMBHAS

AMBHAS is a distributed groundwater model that simulates dynamics of daily groundwater level. The PYTHON code of AMBHAS has been wrapped into a difference equation atomic model in RECORD.

Table Appendix 6. 13: Description of inputs, outputs, parameters and equations used in the AMBHAS sub-model.

Inputs		**Parameters**	**Outputs**	
Potental_net_recharge	Net_recharge_village from net_recharge_village model (m3/day)	RechargeConversionFactor = 1	GWVol	Groudwater volume (m3/m²)
		Sy = 0.21 (specific yield)	h	Groundwater level (m.a.s.l)
		T = 20 (transmissivity)	discharge	Discharge (m3/m²/day)
		doPlot = 0		
		Dt = 0 (time step in seconds)		
		hini = 600 m (groundwater		

		level initial)		
		hmin = 580 m (groundwater level corresponding to 0 discharge)		
		n = 1		
		Par_discharge = 0.9995 (parameter controlling the discharge)		

Equation

```
PixelArea = PlotArea@F1P1+ PlotArea@F1P2+ PlotArea@F2P1+ PlotArea@F2P2;
potential_net_recharge=potential_net_recharge / PixelArea; // convert from m3/day to m3/m²/day
GWVol = max(0., (h - hmin) * Sy * PixelArea);
If (hini<hmin), {
  discharge = (1-par_discharge)*(hini-hmin)*Sy}
else {
   discharge= 0};
h = hini + (potential_net_recharge – discharge)/(Sy*PixelArea);
```

5) Meteo

The meteo model simulates daily and expected rainfalls, carbon dioxide content, and potential evaporation, and radiation, maximum and minimum temperatures.

Table Appendix 6. 14: Description of inputs, outputs, parameters and equations used in the Meteo sub-model.

Inputs		**Parameters**	**Outputs**	
			CO2	Carbon dioxide content (ppm)
			ETP	Potential evaporation (mm/day)
			RG	Radiation (MJ/m²/day)
			Rain	Rainfall (mm)
			RainForecast	Rainfall forecasts (mm)
			Tmax	Maximum temperature (degreeC)
			Tmin	Minimum temperature (degreeC)
Equation				

Modélisation des décisions adaptatives de l'agriculteur : Un modèle économique et décisionnel intégré, avec un cas d'étude en Inde

Dans les régions semi-arides, les systèmes de production agricole dépendent fortement de l'irrigation et font face à des difficultés croissantes (épuisement des ressources naturelles, forte volatilité des prix du marché, hausse des coûts de l'énergie, incertitude sur les changements climatiques). Modéliser ces systèmes agricoles et la façon dont ils s'adaptent est important pour les décideurs politiques afin de mieux évaluer leur flexibilité et leur résilience. Pour comprendre la capacité des systèmes agricoles à s'adapter, il est essentiel de considérer l'ensemble du processus de décision : des décisions sur le long-terme à l'échelle de l'exploitation aux décisions de court-terme à l'échelle de la parcelle. Pour ce faire, cette thèse conçoit un système de production agricole adaptable dans un contexte de diminution de l'eau et de changement climatique. Elle fournit une méthodologie guidant l'acquisition de données, leur analyse et la conception de modèle. Elle présente le modèle de simulation NAMASTE représentant les décisions des agriculteurs, les interactions entre agriculteurs pour l'utilisation des ressources communes et met l'accent sur la rétroaction entre pratiques agricoles et évolution de la nappe phréatique. Le modèle a été initialement développé pour résoudre les problèmes critiques de baisse des eaux souterraines liés aux pratiques agricoles dans un bassin versant du sud-ouest de l'Inde. Sa structure, ses cadres conceptuels et ses formalismes peuvent être utilisés dans d'autres contextes agricoles.

MOTS-CLES : processus de décision; typologie; modèle conceptuel ; programmation stochastique dynamique ; politiques de gestion de l'eau ; changement climatique ; bassin versant du Berambadi.

Modeling adaptive decision-making of farmer: An integrated economic and management model, with an application to smallholders in India

In semi-arid regions, agricultural production systems depend greatly on irrigation and encounter increasing challenges (depletion of natural resources, high volatility in market prices, rise in energy costs, growing uncertainty about climate change). Modeling farming systems and how these systems change and adapt to these challenges is particularly interesting for policy makers to better assess their flexibility and resiliency. To understand the ability of farming systems to adapt, it is essential to consider the entire decision-making process: from long-term decisions at the farm scale to short-term decisions at the plot level. To this end, the thesis conceives a flexible and resilient agricultural production system under a context of water scarcity and climate change. It provides a step-by-step methodology that guides data acquisition and analysis and model design. It proposes a simulation model NAMASTE that simulates the farmers' decisions in different time and space scales, represents the interactions between farmers for resource uses and emphasizes the feedback and retroaction between farming practices and changes in the water table. The model was initially developed to address critical issues of groundwater depletion and farming practices in a watershed in southwestern India. Its structure, frameworks and formalisms can be used in other agricultural contexts.

KEYWORDS: farmers' decision-making, farm typology, conceptual model, stochastic dynamic programming, water management policies, climate change, Berambadi watershed.

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AUTEUR : Marion Robert

DIRECTEURS DE THESE : Jacques-Eric Bergez et Alban Thomas

LABORATOIRE D'ACCEUIL : UMR AGIR 1248 INRA/INP-ENSAT, Toulouse