Future Dynamics of Irrigation Water Demand in the Farming Landscape of the Venice Lagoon Watershed under the Pressure of Climate Change

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Abstract: Climate change impacts on the Venice Lagoon Watershed (VLW), an area of 2,038 km^2 in the north-eastern part of Italy, are expected to be particularly relevant for agriculture, given that approximately two-thirds of the total area is devoted to field crops, horticulture and market gardens. Farmer's irrigation behaviour plays a crucial role for the sustainability of crop productions and water consumption. In this study, an agent-based model is developed to explore how farmers' decisions affect future water consumption in the VLW. The model is an "agentized version" of a soil water balance model based on the FAO-56 procedure. A climatic projection representing the IPCC A1B scenario is used to produce future daily data about relative humidity, precipitation, temperature and wind speed. In order to inform the farmers about the simulated future weather conditions, two types of meteorological services are made available: (1) a bi-weekly bulletin and (2) the seasonal forecasts. The precision of these services varies according to the selected exogenous information scenario which simulates different conditions, from perfect knowledge to poor forecasts. Using the available forecasts, farming agents take adaptation decisions concerning irrigation and crop management on the basis of their own risk and water saving attitudes. Farmer's attitudes are characterized by fuzzy classification depending on age, relative income and crop profitability. Farming agents' adaptation decisions directly affect the crop and irrigation parameters, which in turn affect future water needs of the area. By incorporating available and future meteorological services, the model allows to investigate farmers' decision making process and the consequent future irrigation water demand for the period 2015 to 2030. This paper describes the conceptual model following the ODD+D protocol. Preliminary results are under analysis.

Keywords: Agent-based model; Climate services; FAO-56; Farmers' behaviour; Irrigation water demand.

1   INTRODUCTION

Irrigation water management for higher agricultural productivity is a challenging task and it requires complex decision making tools involving farmers and other stakeholders. An agent-based model can offer an exciting opportunity to model heterogeneous economic behaviour and policy responses from the farmers' viewpoint [Berger 2001]. However, under the situation of future climatic changes, agricultural decision-making becomes more complex when the quality and the quantity of the available water are severe constraints. We assume that, in the near future, climate services could provide a reliable tool to help decision-makers allocate resources in anticipation of poor, fair or good seasons, even at the middle latitudes. Exploring meteorological services and incorporating farmers' behaviour that affect crop yields, an agent-based social simulation can provide a useful tool for adaptation decision making in the context of climate change [Bharwani et al. 2005, Ziervogel et al. 2005]. In order to explore available meteorological services in farmers' decision making process of the Venice Lagoon Watershed (VLW), we

provide an exploratory tool which is developed based on soil-water balance of FAO-56 procedure by Allen et al. [1998]. An "agentized version" of the model was developed in Simile that allows us to understand decision making process of complex socio-ecological system and to investigate how these decisions affect future irrigation water demand of the VLW. The conceptual model description is provided following the ODD+D protocol provided by Müller et al. [2012].

2   OVERVIEW

2.1   Purpose
The purpose of the model is to investigate how farmers' decisions, in terms of crop and irrigation management affect future irrigation water demand, under the pressure of climate change incorporating available and possible future meteorological services. The model provides an exploratory tool that is used to investigate human decision making in a complex socio-ecological system: the agricultural landscape of the VLW, an area of 2,038 km2. The focus is on how certain decisions, supported by climate services can cushion droughts.

2.2   Entities, State Variables, and Scales
The model consists of eight main entities including: farmer, water infrastructure system, irrigation system, grid cell (patch), soil, crop, market and climate. All the entities are presented in the unified modelling language (UML) class diagram of Figure 1.
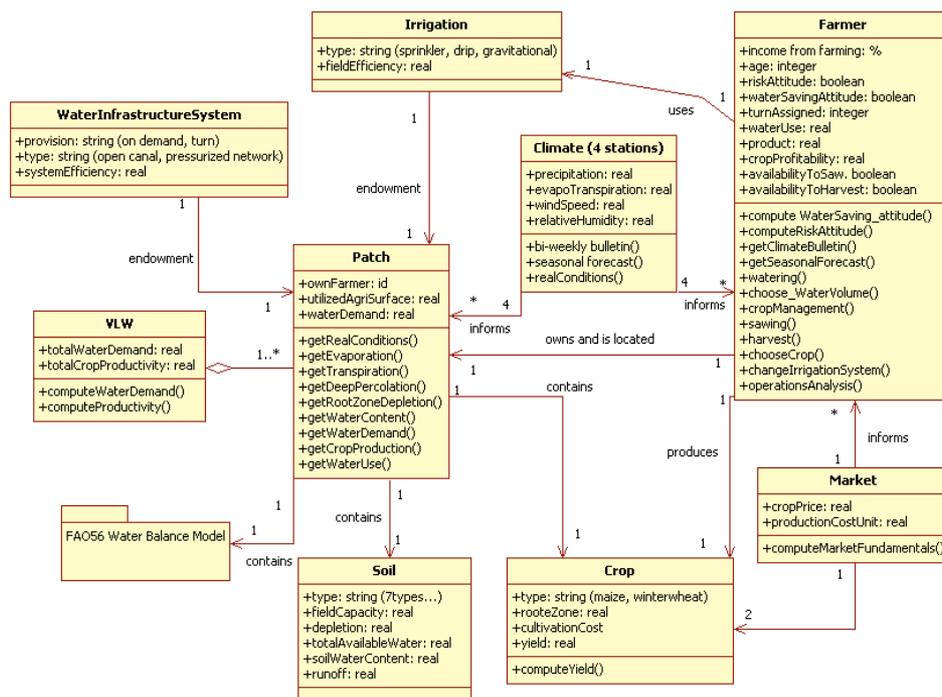

Figure 1 UML class diagram.

Farmers are human agents with given risk and water saving attitudes, affecting the irrigation and crop management decisions. Risk attitude depends on age and the share of income determined by farming. Attitude towards water depends on the crop profitability and the share of income determined by farming.
Water infrastructure system is represented by the provision typology and the related system efficiency. Two types of provisions are available: (1) pressurized system with water on demand, and (2) open canal with water on turn.
Irrigation system is characterized by type and related field efficiency. For the VLW, three types are considered: (1) gravitational, (2) sprinkler, and (3) drip.

Patch is represented by utilized agricultural surface owned by single farmer that contain soil and crop. In the current prototype model, representing the VLW, landscape is segmented into 2,038 grid cells of 1 km^2 each. Overall 74.3% of total area is agricultural, and approximately 90% of it is Utilised Agricultural Area (UAA). The soil entity is characterized by type, field capacity, depletion, total available water, soil water content and runoff. This model implements the logic of the FAO-56 water balance model [Allen et al. 1998] at the patch level (see Figure 2).
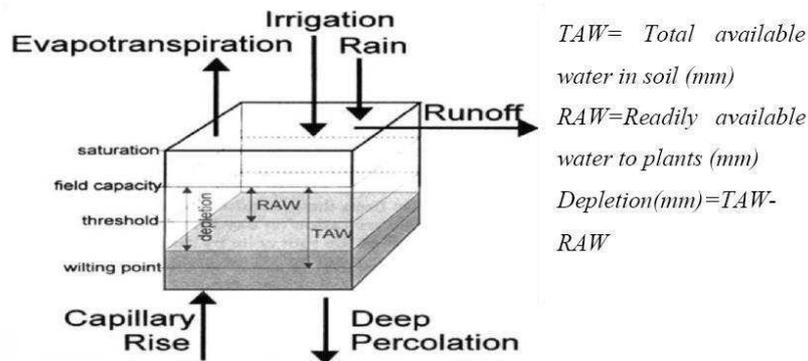

Figure 2 FAO-56 logic of soil water balance (adapted from Allen et al. [1998]).

Crop is represented by type, root zone depth, and yield. Two types of crops are considered in this prototype: winter wheat and maize. The first is chosen to represent rainfed crops with cycles from autumn to late spring and limited climate sensitivity, while the latter is the typical irrigated crop with spring to autumn cycle and high water consumption and sensitivity. The market is described in terms of crop prices and production costs.

The climate entity is represented by four climatic stations characterized with climatic variables (i.e. precipitation, evapo-transpiration, wind speed and relative humidity) available as simulated at daily steps by regional climate models, from which meteorological services information are derived (i.e. bi-weekly bulletin and seasonal forecasting).

The model runs with daily time steps over a period of 15 years (2015-2029). For simplicity in the current version it is assumed that there is a one to one correspondence among the main entities, meaning one patch, one farmer, one crop per year, etc.

2.3   Process Overview and Scheduling

The model process is divided into two levels: tactical and strategic.

The tactical level includes those operations which are carried out on a daily basis and are related to the decision about watering by farmers (i.e. getClimateBulletin, watering, chooseWaterVolume operations) and to the updating of the climatic data and the water balance model at the patch level.

The choice of watering (i.e. yes/no) depends on farmer's perception of the soil water status and own water saving attitude. For farmers who have water on demand the amount of water is influenced by the bi-weekly bulletin. Conversely, farmers who have water on turn do not consider the expected precipitation but they take into account the possibility of saving energy on the basis of the irrigation system in place.

The strategic level includes those operations which take place only at certain moments of the year and represent the core of the farmers' behaviour (see the UML sequence diagram of Figure 3). At the beginning of the year the market computes the market fundamentals. Two options are available: (a) fixed parameters updated at January 2012, and (b) dynamic parameters based on the range of values over the year 2011 [ISMEA 2012]. The seasonal forecast, which contains information about the average distance from the reference values [Cossarini et al. 2008] for forecasted precipitation for the crops critical periods, is produced and delivered. At this point, farmers can choose the preferred crop for that year, according to their risk attitude. This implies different sawing and

harvesting schedules. Maize is sown in March and harvested in November but winter wheat is sown in October and harvested in June. For maize, June and July are the critical months as these are the flowering periods and for winter wheat, September and October are the critical periods (sawing time). After harvesting, farmers analyze their performance in terms of crop productivity and water use. At the end of the year they can plan to change their irrigation system.
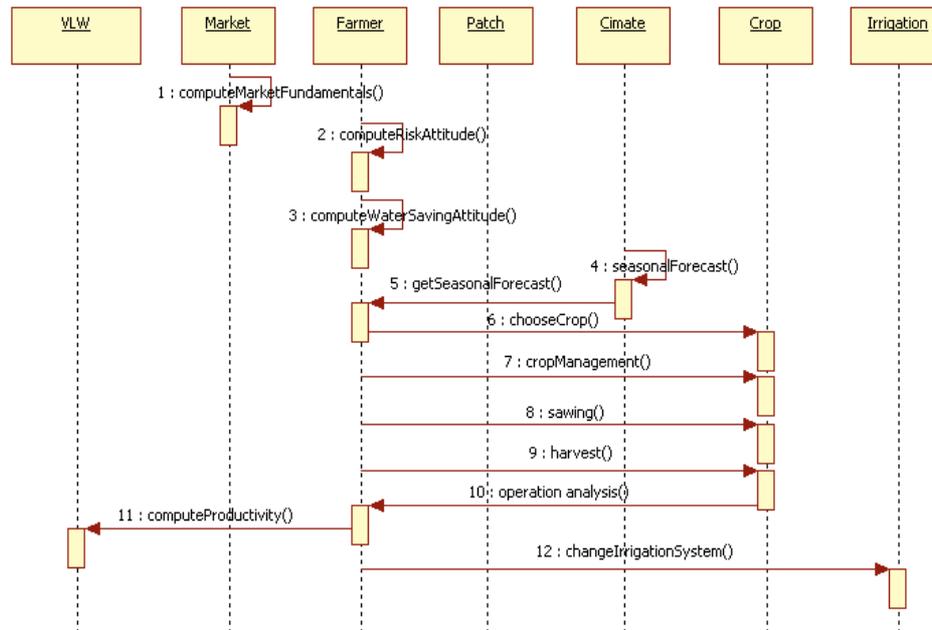

Figure 3 UML sequence diagram of strategic level.

3   DESIGN CONCEPTS

3.1   Theoretical and Empirical Background

Climate change impacts on the VLW are expected to be particularly relevant for agriculture [Salon et al. 2008]. Farmer's irrigation behaviour will increasingly play a crucial role for the sustainability of crop productions and water consumption. Innovative approaches may require substantial private and public investment. In particular it is interesting to investigate the degree of autonomous adaptive capacity given the infrastructure and the meteorological services in place, and how planned adaptation could enhance it (e.g. by changing infrastructure and/or increasing the quality of climate services). Currently the water infrastructure in the VLW is almost entirely based on open canals and 93% of the total area is served by sprinkler irrigation systems [INEA 2009]. Different configurations are adopted in the preliminary version of the model for the purpose of testing heterogeneous conditions, while taking in consideration that certain irrigation systems are more suitable with specific water infrastructures.

At the same time the crop choice is simplified into a dichotomous choice in order clearly distinguish between rainfed and irrigated cultivations. Further, when dynamic market fundamentals are chosen it is assumed that winter wheat renders more stable revenues, while maize may produce higher incomes with low probabilities.

The farmers' decision model largely depends on their classification in terms of risk and water saving attitude. It is well known that age and share of income (i.e. off-farm income) affect risk attitude [e.g. Moscardi and de Janvry 1977]. Conversely there is scarce information on water saving attitude, also because irrigation water cost represents usually less than 3% of total production costs [INEA 2007]. Thus, it is assumed that water saving is pursued only when the crop profitability shrinks as a consequence of saving on other cost elements, such as energy (i.e. pumps needed with sprinkler irrigation systems), and when the farmer income largely relies on farming activities.

3.2 Individual Decision Making

In order to inform the farmers about future weather conditions, two types of meteorological services are made available: (1) the bi-weekly agro-meteorological bulletin, and (2) the seasonal forecasts. Using these services, farming agents take adaptation decisions on the basis of their own risk and water saving attitudes. Tactical adaptation measures concern irrigation water management, while strategic decisions concern the crop choice and the change of the irrigation system.

The bi-weekly bulletin provides the farmers with information about the forecasted cumulative precipitation of the next three days. The sequence of events is predetermined in the simulated weather records, but the quality of forecasts can be degraded, thus moving from a situation of perfect knowledge to bad quality information.

Risk taker farmers with water on demand will decide to irrigate only when the readily available water shrinks to zero. Risk averse farmers with water on demand will water before this stress threshold, and in particular, when the readily available water is inferior to 50% of its maximum point. Both these typologies of farmers will water up to field capacity, taking into account the expected precipitation.

Farmers with water on turn will water depending on irrigation systems. In case of gravitational and drip systems they will irrigate when water content is below 95% of saturation up to saturation (i.e. almost always). In case of sprinkler systems they will irrigate when water content is below the field capacity up to field capacity. In this case the rationale is to save on the energy that sprinkler requires. Both these typologies of farmers do not consider the expected precipitation, because it doesn't make sense to risk a wrong prediction given that water on turn is prepaid.

The seasonal forecast affects the strategic choice of crops as described in Figure 4. If seasonal forecast for maize is critical, risk averse farmers who previously harvested maize will switch to winter wheat. Similarly, if the seasonal forecast for winter wheat is critical, risk averse farmers who previously harvested winter wheat will switch to maize.
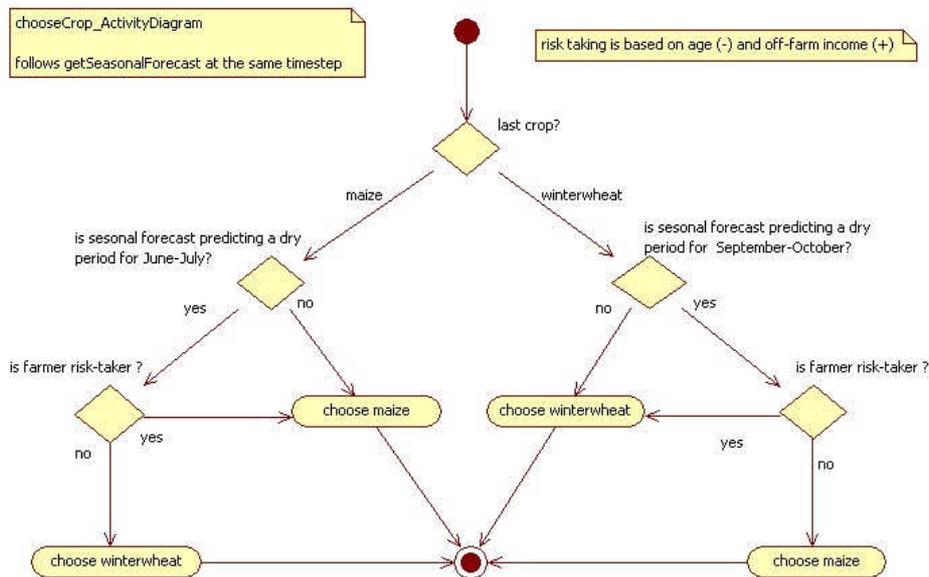

Figure 4 chooseCrop UML activity diagram.

Further, farmers can choose to change the irrigation system on the basis of the existing infrastructure, in order to improve the combined system and field efficiency. It is assumed that gravitational is the first best choice when the infrastructure is open canal, while sprinkler is the target when the infrastructure is pressurized system. In few cases farmers will opt for drip irrigation systems. Probability rules affect the year in which the eligible farmers can take this decision. There is a time lag of two years between the decision and the new system in place.

3.3 Learning
In this first model version no individual or collective learning is included in the decision process. However, it is planned to include memory about forecasts quality and an individual learning process that can affect the farmer choice to follow or not the forecasts.

3.4 Individual Sensing
Farmers endogenously know the water balance, the water volume delivered to their fields, and the crop yield from the FAO-56 submodel. They also exogenously perceive information on simulated climatic parameters as well as the water infrastructure system in place, at the patch level.

3.5 Individual Prediction
Farmers predict climatic conditions by means of the meteorological services. The prediction is erroneous because it is affected by a degradation parameter, which is an error of variable intensity applied to simulated data representing the A1B IPCC climatic scenario.

3.6 Interaction
There is no interaction among farmers, but each farmer interact with his own each patch in which climatic records as well as other records (soil, crop, irrigation system, and water infrastructure systems) are stored.

3.7 Collectives
The water infrastructure system is collectively shared.

3.8 Heterogeneity
Farmers are heterogeneous in terms of risk and water saving attitudes because they have different age, relative income from farming and crop profitability. At the patch level, there are various degrees of heterogeneity: 2 alternate crop types, 7 soil profiles, 4 weather stations of reference, 3 types of irrigation systems, 2 types of water infrastructure systems.

3.9 Stochasticity
Sawing and harvesting periods of maize and winter wheat are determined using a random function considering the fact that they are not sown and harvested on same day of each year. Stochastic processes are also included in the choice of changing the irrigation system in order to avoid all the farmers with same configuration to act at once. Further, with dynamic market fundamentals the price of winter wheat is normally distributed, while the price of maize has a long tailed Poisson distribution.

3.10 Observation
At the end of each year from 2015 to 2029, annual water demand and annual crop yield are collected for each patch, which is then aggregated for the whole VLW level. It is thus possible to compare future water demand and crop yield for the study area, under different model configurations regarding: (1) initialization, (2) water infrastructure in place, (3) climate services quality.

4 DETAILS

4.1 Implementation Details
First, the FAO-56 model has been implemented in Simile (http://www.simulistics.com) a system dynamics and object-based modelling and simulation software for complex dynamic systems [Bhandari 2011]. The "agentized version" has then been developed as described in this paper.

4.2 Initialization
The model is initialized with 1,514 farmers, one per agricultural grid cell. Farmers' age and share of income from farming are distributed according to regional

statistics of VLW [Bojovic et al. 2012]. For simplicity the utilized agricultural surface is set at 90% of patch area in every cultivated patch.

Differently from current real conditions (99% open canal) it is assumed an initial distribution of 50% per type of water infrastructure systems. The probability distribution of irrigation systems depends on the infrastructure in place: 10% gravitational, 60% sprinkler, 30% drip, for pressurized system, and 60%, 30%, 10% for open canal.

4.3 Input Data

Simulated climatic conditions are produced with the COSMO-CLM model considering the IPCC A1B scenario [Scoccimarro et al. 2011].

4.4 Submodels

Crop, soil, climate and irrigation parameters are input parameters of the sub-model FAO-56 that operates at the patch level [Allen et al. 1998].

Risk and water saving attitude are computed by means of a hypertrapezoidal fuzzy function [Kelly and Painter 1996]. Regarding risk, it is employed a bi-dimensional fuzzy membership function that assumes an hypothetical 20 years old farmer (j) producing 0% of his income from farming activities as the perfect risk taker (i.e. ρ value = +1), and a 70 years old farmer (i) with 100% of his income from farming, the perfect risk averse (i.e. ρ value = -1). A farmer is considered risk taker for $\rho >$ 0.1, where the function is:

$$\rho_{i|j}(\Lambda) = \frac{|\vec{v}_i|^2 - |\vec{v}_j|^2}{|\vec{v}_{ij}|^2}$$

Λ is the farmer on which we want to compute the risk attitude, identified by a certain age and share of income. $\vec{v}_i$ is the vector from Λ to farmer (i), $\vec{v}_j$ is the vector from Λ to farmer (j), and $\vec{v}_{ij}$ is the vector from farmer (i) to farmer (j).

A similar structure is employed for water saving attitude but the variables are: (1) crop profitability (i.e. cost of production / value of production, belonging to the domain [0.5, 1.5]) and (2) share of income from farming.

5 CONCLUSION

Mainstream economics is usually not interested in the emergent properties developing within heterogeneous and spatially distributed socio-ecological systems, while the observation of autonomous adaptation processes demonstrate that bounded rationalities, imperfect information, varied utility functions, together with the effects of spatial topology, communication networks and social learning play remarkable effects on the overall behaviour of the system: in this case the consumption of water resources for irrigation purposes in the Venice Lagoon Watershed. The research presented herein in its preliminary stages is expected to contribute for the exploration and learning purposes with original and innovative approaches to provide insights on current farm management and projections on future autonomous adaptation processes, which can be improved through ground based observation and other validation approaches.

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