8 Challenges and opportunities for historical irrigated agricultural systems in Mediterranean regions

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Andrea L. Balbo, José María García Avilés, Johannes Hunink, Francisco Alcón, Juan Esteban Palenzuela Cruz, Julia Martinez-Fernández, Arnald Puy, Juan Miguel Rodriguez Lopez, Katharina Heider, Rodrigo García Abenza, and Jürgen Scheffran

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Abstract

Historical irrigated agricultural systems in Mediterranean regions provide a long record of sustainability and adaptation to changing climatic, environmental, and social conditions. These agricultural systems are currently confronted with challenges that may threaten their persistence over the next decades. Here, we propose a first assessment of strategies and opportunities that may contribute to the continued sustainable development of historical irrigated agricultural systems. Our assessment is based on experience gained within the agricultural community of Ricote (Murcia, Southeast Spain), in consultation with local stakeholders and external experts.

KEYWORDS: *Agriculture, irrigation, meteorology, water, GIS, CO2 emissions, smart rural development.*

Introduction

As climate warming intensifies in Mediterranean regions, historical irrigated agricultural systems are increasingly exposed to water shortages, pauperization, and depopulation (Kummu et al. 2010). Such conditions are threatening the existence of a long tradition of practices for managing water scarcity in Mediterranean irrigated rural contexts (Balbo et al. 2016). The selected case study of Ricote (Murcia, Spain) provides a privileged setting to assess the challenges and opportunities of these historical irrigated agricultural systems. Known as one of the earliest irrigated agricultural system of Andalusian origin in Europe (Puy and Balbo 2013), Ricote has been sustaining the local community for over a millennium, withstanding important climatic (the transition from the warm Medieval Climate Anomaly to the cold Little Ice Age) and social (the Crusades and the industrial and informatics revolutions) events. Within the global trend of irrigation expansion and modernization, insights obtained from the study of such cases as Ricote can help identifying key challenges, strategies, and opportunities in similar contexts. Meanwhile, our contribution expands the richness of international case studies focusing on the sustainability of irrigation-based food systems (Agoramoorthy and Shu 2015; Tabbal et al. 2002; Zhang and Zhao 2013). Specifically aimed at historical irrigated agricultural systems, our case study adds to the enhancement of sustainable development and social inclusiveness in rural regions at large, in line with the principles of the Europe 2020 growth strategy (Copus et al. 2011; Dijkstra and Poelman 2008; EC 2010).

Due to environmental specificities such as its endemic lack of water or the arid and semi-arid climate, as well as to its inherent historical trajectory, South Europe, led by Spain, is at the forefront of irrigated agriculture, technology, and innovation (Soto-García et al. 2013a). The importance and antiquity of irrigated agriculture and water management institutions in East and Southeast Spain is attested by the inclusion of Irrigators' Tribunals (The Council of the Wise Men of Murcia or the Water Tribunal of València, both dating back to al-Andalus) in the UNESCO's list of intangible heritage (Inscription: 4.COM 13.70, 2009). This situation is the result of a long tradition, rooted in the Middle Ages, when irrigated agriculture constituted the main food production strategy of Arab-Amazigh/Berber groups proceeding from North Africa (Puy and Balbo 2013). As a general rule, irrigation systems of Arab-Amazigh/Berber origin were further extended following the feudal conquest of al-Andalus (10th-15th centuries), when Christian settlers introduced an economy specialized in vines and cereals, prioritizing the use of water mills for milling and irrigation purposes (Kirchner 2009; Torró 2006). Further extensions of existing irrigation schemes and the construction of new ones have continued to the present day. In a simplified way, two models of irrigated land can presently be found in Spain, which represent the two ends of a gradient. The first model is that of historical irrigated agricultural systems, usually located near springs or along river valleys. The second model is that of modern, business-oriented irrigated systems. However, their noticeable increase in the last decades has raised sustainability concerns (Martínez-Fernández et al. 2004).

The specific case study of Ricote is embedded in a region currently characterized by stable social and political conditions. Such conditions have greatly favored the development of full collaboration between stakeholders, including scientists, local authorities, specialized technicians, and agriculturalists.

Said that, challenges related to current and foreseeable climatic trends in Southeast Spain are observed in arid and semi-arid regions across the Mediterranean, including e. g. the Near East and sub-Saharan Africa. Likewise, the analyzed historical irrigated agricultural system is widespread across Mediterranean regions involved in the medieval westward expansion of the Muslim world, where it constitutes, to the present day, a cornerstone of local rural economies.

In this sense, insights gained in Ricote are of value in conflict-sensitive regions across the Mediterranean, where the consolidation of local rural communities and economies, leveraging on existing technical, cultural, and environmental assets, is of paramount importance to address some of the greatest challenges of the day, including climate-related distress, social unrest, and mass migration.

In this paper, after describing the historical evolution of Ricote, we proceed to identifying the main foreseeable challenges facing this agricultural and ecological system in the current context of climate warming, increasing water scarcity, rural depopulation, and energy regulations (FAO 2015; Iglesias et al. 2012). We then propose two sets of possible climate adaptation responses, information-driven and infrastructure-driven, considering their social and technological components (Crane et al. 2011; Howden et al. 2007). We end by discussing the potential of information-driven solutions within the framework of smart sustainable rural development (FAO 2013; Naldi et al. 2015; Thissen et al. 2013). Our discussion is framed in the recent understanding that potential solutions for improving water and land management should consider the social organization of water sharing, traditional knowledge about climate, agriculture and ecology as well as digital technologies with potential to facilitate water management tasks (Naldi et al. 2015).

Context and Methods

As case study, we scrutinize the historical evolution of the irrigation scheme of Ricote (Murcia, Spain), from its medieval origins to the present-day. The main strategy applied is case study research to capture distinctive traits in the evolution of the specific context of the Ricote irrigation system (Yin 2013). The village of Ricote (UTM

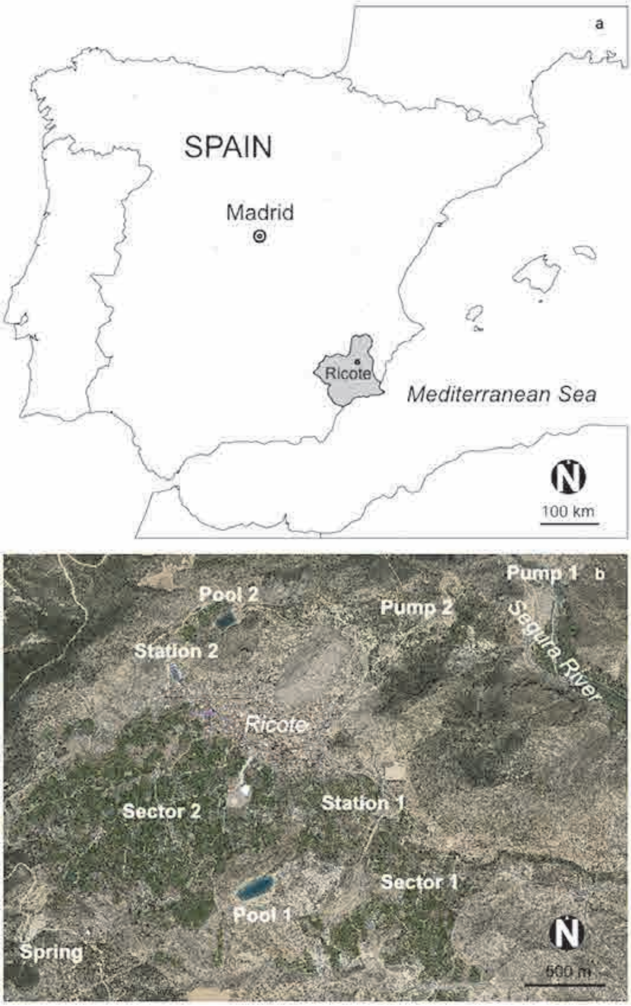

Figure 1: (a) Location map (Murcia region in grey), (b) orthophoto map of Ricote with approximate positioning of main components of the DI system schematized in Figure 3.

30S, 642980.39E, 4223751.54N, Murcia, Spain, Figure 1) and its associated cropland lie in a hoya, a flat basin surrounded by mountains, approximately 235–375 m above sea level (Puy 2014). It can be defined as a huerta. The term defines irrigated areas, many of them of historical origin, where traditional irrigation techniques have been used to tap water from rivers, springs, or underground. Traditionally, these open agricultural landscapes have been characterized by high crop diversity (Mata Olmo and Fernández-Muñoz 2004; Meeus 1995; Meeus et al. 1990). Together with four other villages found along the Ricote Valley, Ricote constitutes a comarca (consortium of villages), and has been recognized as one of the agricultural landscapes with the highest socio-economic, environmental, and cultural value in Spain (Egea-Sánchez et al. 2008).

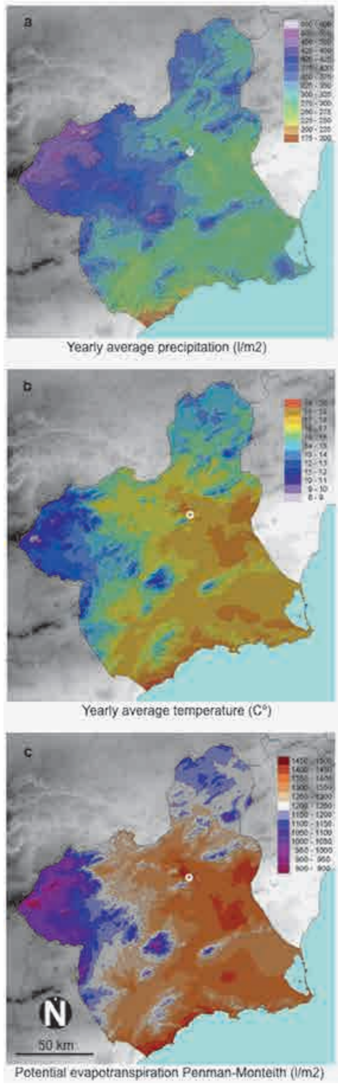

Figure 2: Climatic maps for Murcia region (the position of Ricote is indicated by the white circle).

Climate in Ricote is semi-arid. Average data, derived from the Climatic Atlas of the Murcia Region for the period 1971–2000, indicate average summer (JJA) temperatures of 25.5 °C (annual average summer maximum 31.1 °C) and average winter (DJF) temperatures of 10.2 °C (annual average winter minimum 5.4 °C). Annual potential evapotranspiration (PET) amounts to approximately 1350–1450 l/m^2 and annual average rainfall to 343.1 mm (Garrido Abenza et al. 2013) (Figure 2)[1]. Data from the local AEMET meteorological station La Calera (covering the period 1949–2015, excluding the incomplete series for 2007 and 2010) indicate that rainfall in the region is characterized by a significant annual variance, with lowest annual average rainfall of 140.4 mm recorded in 1970 and highest annual average rainfall of 884.4 mm recorded in 1989. This constitutes a standard deviation of 126.9 mm. Monthly variance in precipitation is also significant, with lowest monthly average rainfall of 3.9 mm in July and highest monthly average rainfall of 43.9 mm in December, i. e. a standard deviation of 11.8 mm.

The origins of the Ricote irrigation system in the Andalusian period (10th–13th centuries AD) have been defined using geoarchaeological, historical, and radiometric methods (Puy 2014; Puy and Balbo 2013; Puy et al. 2016a).

1 (a) annual average precipitation (l/m^2), (b) annual average temperature (C°), (c) potential evapotranspiration based on Penman-Monteith (l/m^2). Data source: AEMET Agencia Estatal de Meteorología. Ministerio de Agricultura, Alimentación y Medio Ambiente (State Meteorological Agency. Ministry of Agriculture and Environment).

Information on the more recent evolution of the Ricote agroecosystem has been retrieved from the study of the archives of the Comunidad de Regantes de Ricote (Ricote Irrigator Community). These documents include communications with the government, legal disputes, financial administration, technical reports, and minutes of regular internal meetings from 1957 to the present. Such archives provide, among others, information on water allocations to the community, infrastructure implementations, as well as energy and water requirements for irrigation. Regular participatory processes, including in-depth interviews with members of the irrigator community were conducted to complete and corroborate archival information, complementing the case study strategy (Boyce and Neale 2006). A participatory focus group was organized between members of the irrigator community and external experts to identify key challenges, strategies, and opportunities.

The historical evolution of the Ricote agricultural system

Historical irrigation schemes have been upgraded through time, consistently integrating available innovations and providing examples of human-environment interaction, human adaptation to external pressure, and sustainable development. In general, the size and complexity of the irrigation infrastructure shared by the Ricote Irrigator Community has increased over time. Successive hydraulic systems deployed in Ricote have all been characterized by their costly installation and maintenance, requiring the joint effort of the community. Water and water distribution systems have thus been historically managed in a participative way. In spite of possibly contrasting particular interests and conflicts, farmers have had to organize and agree on common strategies in order to implement successful irrigation schemes, as they do in the present day. The historical evolution of the Ricote agricultural system is summarized hereafter in terms of: (3.1) an extension of the irrigated area, (3.2) increases in volume of water available for agriculture, and (3.3) the implementation of water distribution systems.

Extension of irrigated area and crops cultivated

In the 10th-13th centuries AD, the initial irrigated area of Ricote extended over approximately 2 ha, and reached a surface of c. about 50 ha around the time of the feudal conquest of al-Andalus (completed in 1492 AD). Following further expansions, the irrigated area extended over 120 ha in 1614 AD (Puy 2014). In 1957, following the concession of water from the nearby Segura River the maximum extension of the irrigated area was set at about 190 ha. Of those, close to 30 ha were converted into constructible areas between 1957 and 2007. The extension of the irrigated area was further revised in 2007, integrating new land to reach the current maximum extension of irrigated cropland of 184.492 ha. In the second half of the 20th century, the irrigated area was divided into two approximately equal sectors: sector 1 and sector 2. Over this surface, Ricote counts with approximately 2400 parcels, distributed among roughly 600 landowners. As for crops cultivated in Ricote, historical texts revised by Puy (2014) inform us that plum, olive, apricot, orange, lemon, lime, fig and cherry trees, myrtle, grapevines, pomegranates, cedar, and alfalfa were cultivated between 1495–1505. By 1613, Ricote had specialized in cash crop production, and olive trees had become the primary crop along with mulberry tree for silk production. The current production of lemon trees as cash crop was initiated in 1962.

Increases in volume of water available for agriculture

Ricote has known successive increases of the overall volume of water available for agriculture. Since its creation, the Ricote agricultural system has relied on the perennial spring El Molino (390 m above sea level, Figure 1b), supplying a consistent flow of approximately 13 l/s, equal to a total of close to 410 000 m^3/year (García-Avilés 2000). Minor water points (including Paul, Balsas, Balsones) have subsequently been captured, potentially accounting for an additional 6 l/s. In addition, Ricote has a concession to withdraw up to 1 035 000 m^3/year from the nearby Segura River since 1957, granted by the Confederación Hidrográfica del Segura (CHS, Hidrographic Confederation of the Segura River), part of the Ministerio de Agricultura, Alimentación y Medio Ambiente of the Spanish Government (CHS 2016). Water allocated may vary on an annual basis depending on precipitation patterns and on political agreements. Water extraction began on 30 April 1962, when the irrigator community deployed a first pump (at about 135 m above sea level), which was replaced in 1982, and again in 2013. Virtually inexistent before the deployment of pumps, overall energetic consumption is now almost 982 762.29 kWh/year (i. e. nearly 1 GWh/year).

Implementation of water distribution systems

Over time, the construction of infrastructure regulating the timing and access to water in Ricote has promoted a similar evolution with regard to the access to increasing volumes of water. Since its creation, Ricote has relied on a dense and growing network of channels and water locks (Puy 2014) and on irrigation schedules to regulate access to water. Between the 17th century and the 1950s, 45 days elapsed before all users received

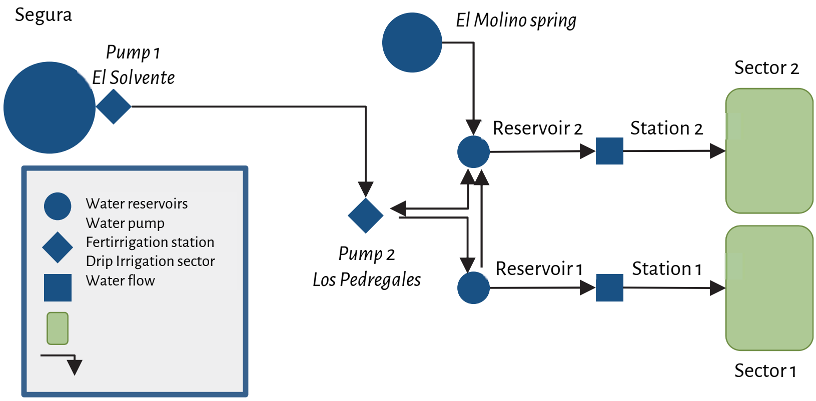

Figure 3: Scheme of the main components of the DI system in Ricote .

one turn of water from the local spring, i. e. until a full tanda was completed (Cabrera and Arregui 2010). Irrigation schedules run continuously and irrigators had to be available 24/7. A bifurcation of the main irrigation channel was implemented in the second half of the 20th century to halve irrigation times and to reduce night irrigation shifts. Since 1982, the community of Ricote posesses a water reservoir (Reservoir 1, Figures 1b, 3) with a capacity of 15 000 m³. In 2007, an additional water reservoir (Reservoir 2) with a capacity of 45 000 m³ was built. In parallel, a centralized electronic Drip Irrigation (DI) scheme was implemented (Figure 3). Nearly 90 % of the parcels in Ricote (1651 out of 1835) were equipped with DI in 2015 (Puy et al. 2016b). Irrigators who equipped their plots with the DI system discarded the traditional hydraulic infrastructure. Currently, water from the Segura River and from the local spring is accumulated in the local reservoirs and distributed to the fields through the DI scheme. DI schedules are planned on a yearly basis and all plots are served with water within the same day.

Two independent networks of pipelines, tubes, and emitters distribute irrigation water across the irrigations scheme: (a) Sector 1 to the West, (b) Sector 2 to the East. A total of 105 station-cabinets spread across the hydraulic system is equipped with consumption meters and mechanical and electronic devices to control counters and inform the irrigator community on breakdowns. The electrical network connects the station cabinets with the irrigator community computer.

The irrigator community computer regulates the functioning of the system, controls the station cabinets, and stores all data relative to consumption and land tenure.

A webpage and related mobile application for landowners affiliated to the irrigation scheme allows irrigators to remotely consult water consumption and other relevant information.

Foreseeable challenges

While improving the economic and working conditions of the local community, historical implementations of the Ricote irrigation scheme are showing possible underlying flaws and potential drawbacks in the face of current and forthcoming social and environmental challenges (Kummu et al. 2010; IPCC 2012; Tacoli and Mabala 2010). Repeated exchanges between members of the Ricote Irrigation Community, local policymakers, and external specialists led to the following catalogue of identified challenges for Ricote over the coming decades: (4.1) increasing water scarcity, (4.2) energetic dependency and CO2 regulations, (4.3) outmigration and loss of knowledge, and (4.4) technological and innovation dependency.

Increasing water scarcity

Over the coming decades, predicted climate change with increasing temperature and precipitation extremes, may jeopardize recent efforts and implementations made in agriculture, including the introduction of mechanical irrigation technologies such as DI (IPCC 2012). In the specific case of Ricote, which can be considered climatically representative for South Europe, modeling of future water availability for the Tajo-Segura River transfer system predict average water shortages of more than 20 % before 2050, accompanied by harsher dry extremes (Estrela et al. 2012; Garcia Galiano et al. 2015; Vargas-Amelin and Pintado 2014). In such scenario, any improvement in the efficiency of water use for agriculture is fundamental for irrigated schemes in drylands.

Energetic dependency and CO2 regulations

The lack of an international agreement since the Kyoto Protocol remains a source of uncertainty regarding the regulation of carbon emissions (Perdan and Azgapic 2011). For example, carbon regulations remain vague for the airlines industry (Engau et al. 2011), and the agricultural sector was explicitly not included in the European Emissions Trading System (EU ETS) (Brandt and Svendsen 2011). However, being responsible for an important portion of global CO2 emissions, the agricultural sector is a key subject of emerging mitigation regulation schemes (IPCC 2012). Specifically, irrigated agriculture has significant energy requirements that add to direct emissions, which deserve being assessed (Soto-García et al. 2013b). Taking advantage of the preexisting historical irrigation network plan, water distribution within the DI scheme of Ricote, from the water reservoirs to the fields through the two fertirrigation stations (i. e. irrigation stations distributing a mix of water enriched in fertilizers), relies mostly on gravity with negligible energetic requirements. However, a major energetic requirement concerns the extraction of pressurized water from the Segura River into the local water reservoirs. To this aim, yearly energetic consumption from the two water pumps and fertirrigation stations can be approximated to almost 1 GWh/year, alimented with electricity from the national grid. Such consumption implies CO_2 emissions of close to 381 311.77 kg/year (IHC 2011).

Outmigration and loss of knowledge

Rural-urban migration is a global phenomenon contributing to the aging of populations in rural areas (Tacoli and Mabala 2010), widely attested in Europe and Spain (Geraghty et al. 1998; Pinilla et al. 2008). Within this context, the agricultural community of Ricote is rapidly aging, facing serious challenges of a sustainable transmission and take-over of knowledge between generations. Ricote had a steady population of nearly 3000 inhabitants between 1900 and 1950, decreasing under 2000 in the 1980s, further steadily decreasing in recent years, and reaching a historical low in 2016, just above 1300 people (INE 2017).

External technological and innovation dependency

With the introduction of ever more mechanized and automated solutions, the dependency of the community on external know how has grown. At present, for example, one of the strongest external dependencies concerns the software used to manage the centralized DI control system. In fact, while most mechanical and electronic components of the DI system can be found in non-specialized markets, the software used in Ricote was specifically designed by the company responsible for the maintenance of electronic parts within the DI system. As a result, the community of irrigators is limited in its capacity to upgrade the DI control system and implement in-house low-cost developments.

Discussion: Strategies and opportunities for continued sustainability

Here, we combine the experience of local stakeholders and external experts to propose a first expert assessment of strategies and opportunities for the long-term sustainability of the historical irrigated agricultural systems in Ricote. While challenges in Ricote are similar to those faced by small agricultural communities in other Mediterranean regions and in drylands worldwide, further and case-specific assessments are required before implementation. Consultations between members of the Ricote Irrigation Community, local policy-makers, and external specialists led to the following catalogue of identified strategies and opportunities for Ricote over the coming decades: (5.1) reduce water dependency, (5.2) prepare the transition to low CO_2 emissions, (5.3) fill generational and knowledge gaps, and (5.4) promote in-house innovation.

Reduce water dependency

Three strategies were retained for consideration in Ricote to counter increasing water scarcity.

Water savings using real-time meteorological information. We estimate that fertirrigation could be offset by approximately 7.5 %, by dynamically factorizing actual precipitation (which is 343 mm/year) into current agro-hydrological models and fertirrigation schedules. Such implementation would imply average annual savings of more than 52 500 m^3, i. e. 17 325 € considering current fertirrigation cost of 0.33 €/m^3 (0.23 €/m^3 for water and 0.10 €/m^3 for fertilizers). These estimates are obtained from current yearly water use for fertirrigation in Ricote of about 700 000 m^3/year, defined by agronomists for the predominant crop type lemon tree Verna on the assumption of zero precipitation. In order to allow the development of new dynamic agro-hydrological models, a local meteorological station is being developed that has the capability to send real-time data to the central computer controlling the DI system (Figure 3). The new agro-hydrological models will be designed in accord with end-users to systematically stop fertirrigation after concentrated precipitation events, following irrigation decision support system models developed elsewhere (Tapsuwan et al. 2014). Agronomists suggest that the shortage in fertilizers caused by these short interruptions in fertirrigation flow will have no negative effects on plant growth (Domingo et al. 1996).

Reduction of evaporation from the water reservoirs. We estimate that covering of the water reservoirs in Ricote could reduce water loss to near zero. This operation would however lead to only minor annual water and economic savings, up to 1.5 %, corresponding to 3450 €/year. Our estimates are obtained considering the approximately 1.5 ha surface of the two shallow (<5m deep) reservoirs in Ricote, for which average yearly evaporation is about 15 000 m^3, i. e. an evaporation of close to 1000 mm/year for semi-arid Mediterranean climates (Harwell 2012; Martínez Alvarez et al. 2008). Based on previous economic assessments for the deployment of shade-cloth covers for agricultural irrigation reservoirs in the Segura River Basin, several years would be required to offset initial costs (Martínez Alvarez et al. 2009).

Increase in the capacity to capture and store rainwater. We estimate that the development of Managed Aquifer Recharge (MAR) would significantly increase the water storage potential for the irrigator community. However, assessing the full potential of a MAR scheme depends on an extensive hydrogeological evaluation of available groundwater reservoirs. Geoengineering assessments for the potential development of MAR have previously been undertaken in Spain to redirect excess runoff towards artificial sinkholes and to recharge the aquifer using surficial channels (DINA-MAR 2016). However, there has been no MAR project implemented so far in the Segura Basin to our knowledge. In addition, the possibility for rainwater harvesting is severely restricted by the Confederación Hidrográfica del Segura.

Prepare transition to low CO_2 emissions

Two strategies were retained for consideration in Ricote to address energetic needs and related CO_2 emissions. However, a detailed assessment of direct and indirect emissions is necessary before implementing such infrastructure. Furthermore, such assessment would provide a clear anticipatory strategy for foreseeable but uncertain regulation (Engau et al. 2011).

Install solar panels on top of the existing water reservoirs. We estimate that Ricote's energetic requirements for agriculture could be offset with renewable solar energy by covering water reservoirs in Ricote with solar panels. Our first approximation suggests that covering the 1.5 ha of reservoir surface available in Ricote with solar panels would potentially produce up to 1.34 GWh of solar energy per year (Energy Manager Today 2016). Such production would offset current agricultural energetic requirements by approximately 0.34 GWh/year. Besides providing solar energy, this solution would reduce water loss through evaporation from the reservoirs, without implying loss of prime agricultural soil and forestland.

Design of an energy adaptation strategy. Considering that legislation is likely to be modified in the near future, the exercise of designing a full energy adaptation strategy provides an opportunity to capture the maximum amount of information on regulation processes and constraints, favoring a rapid transition when new carbon emission regulation appears. The first irrigated agricultural systems to implement such strategies will set the standard for irrigated agriculture schemes based on low CO_2 emissions. Nevertheless, current energetic regulations in Spain provide low incentives for renewable solar energy in the agricultural sector, hampering the coexistence of solar energy and the national grid energy.

Fill generational and knowledge gaps

Two potential strategies have been retained to address rural depopulation as well as intergenerational knowledge and information flow. They provide the opportunity to ease the training of the next generation of local stakeholders, reduce the loss of traditional knowledge (TK), and diversify the local economy based on the valorization of new ecosystem services (ES) (Berkes et al. 2000; Gómez-Baggethun et al. 2010; Martínez-Fernández et al. 2009, 2013).

Digital and participative mapping of the irrigated agricultural scheme. We estimate that the digitalization of local knowledge and information using available Geographical Information Systems (GIS) would help support decision-making while reducing the loss of information on land-tenure, water-management, and land-use. Digital mapping technologies could be used to train young administrative, management, and technical staff, an issue the community is facing due to the imminent retirement of several members of its governing body (Hossain and Sadat 2006). To this end, the records of the Irrigator Community are currently being merged with digital cadastral maps of the Ministry of Agriculture (SIGPAC 2016). This fusion of local data with digital mapping will remove one of the major drawbacks for generational takeover, i. e. the difficulty to visualize complex irrigated agro-ecosystems and underlying social, economic, and ecological processes. Overall, digital technologies facilitate community participation in decision-making and governance (Pérez et al. 2011), while strengthening risk awareness (Berkes et al. 2000; Copus et al. 2011; Dijkstra and Poelman 2008; Gómez-Baggethun et al. 2010). Potential applications of dynamic digital mapping include: (a) the critical management of land tenure transactions to reduce land fragmentation, land tenure, DI system complexities, and associated risks (Baños-González et al. 2015; Heider et al. 2018), (b) the planning of water management priorities in case of water shortage, e. g. establishing emergency irrigation patterns based on cultivar and soil characteristics, and (c) decision-making support for development planning, including e. g. the creation of visitor circuits or the definition of biodiversity conservation areas (Martínez-Fernandez et al. 2009).

Development of benefits based on supplementary ecosystem services (ES). We consider that, by providing facilitated access to information and enhancing overall information sharing, digital technologies will increase the community potential to develop new economic activities and benefits based on the development of supplementary ES. In the nearby huerta of Murcia, more than 30 types of ecosystem were identified, highlighting the potential multi-functionality of such agricultural and ecological landscapes (Gutiérrez González et al. 2015). These can be summarized in provisioning, regulatory, and cultural ecosystem services: (a) provisioning services, i. e. historical irrigated lands are very productive and possess a proven robustness in the face of changes in water availability (Pérez et al. 2011; Gutiérrez González et al. 2015). Such productivity can be oriented to the provision of quality food for the local market (Egea-Sánchez et al. 2008), (b) regulatory services, i. e. historical irrigated lands contribute to maintaining fertile soils, a non-renewable and scarce natural resource, particularly in arid and semi-arid climates (Martínez-Fernández et al. 2013). Moreover, these agricultural systems improve microclimatic conditions, a valuable service under current climatic conditions (Gutiérrez González et al. 2015), (c) cultural ecosystem services are a constituent of historical agricultural and ecological landscapes, preserving traditions and culture, functionalities that have been increasingly recognized in historical irrigated lands (Gutierrez González et al. 2015; Martínez-Fernández et al. 2013). These agricultural systems generate landscapes of high scenic value (Egea-Sáchez et al. 2008). Historical Mediterranean huertas may have lost part of their economic functionality (Rossi 1993, Vos and Meekes 1999), but measures for their viable and sustainable preservation have been taken, including e. g. the elaboration of a Red List of Threatened Mediterranean Landscapes (Rossi 1993).

Promote in-house innovation

At least two possible pathways were identified to address the shortcomings posed by external technological and innovation dependencies.

Integration of solutions involving low degrees of mechanization, low energy consumption, and the integration of traditional knowledge (Barnett and O'Neill 2013). The deployment of tried and tested solutions minimizes the risks of maladaptation, while ensuring low levels of external dependencies. Such solutions can be evaluated within a rich body of locally developed knowledge, made accessible through the development of digital repositories (5.3).

Training of local personnel. Local investments in the training of local youth in more technologically demanding solutions can significantly reduce dependencies on external technology while promoting innovation and qualified employment opportunities within the community. The implementation of water-saving strategies (5.1) would provide the necessary resources to internally fund such training. In the longer term, innovative start-ups can develop within the framework of smart rural solutions (Naldi et al. 2015).

Conclusions

Within the current context of modernization in irrigated agriculture, historical irrigated agricultural systems offer a unique opportunity for the study of the potential adaptive responses that small agricultural communities may consider in the face of foreseeable challenges affecting water consumption and food production in drylands around the world. Water shortages, climate variability, rural-urban migration, market competition, ageing of rural populations, and poor innovation could undermine the viability of historical irrigated agricultural systems. To address such challenges, we have used the case study of Ricote to explore solutions and opportunities aimed at sustaining irrigated agricultural systems that are attractive, viable, and resilient. Opportunities and solutions emerging from our specific context can be summarized in information-driven and infrastructure-driven. Infrastructure-driven solutions, such as solar power plants or MAR systems, require high initial investments. In contrast, information-driven solution, such as dynamic agro-hydrological models and relational mapping, can be implemented at low cost. Leveraging on existing knowledge, management, and governance structures, information-driven solutions have the potential to increase the responsiveness and flexibility of historical irrigated agricultural systems.

Based on the principle that knowledge and innovation are the driving forces for future viability, the emphasis of our work is on knowledge and information-driven innovations, facilitated by the use of digital technologies, for the preservation of local traditional knowledge, the development of sustainable and growth-oriented economic strategies, and the empowerment of rural communities. Acting on the governing rather than the biophysical limitations of irrigated agro-ecological systems, information-based solutions (i. e. smart solutions) show the highest potential for adaptation and flexibility in the face of change. Such solutions increase autonomy and capacity for self-organization within communities, critical attributes to develop dynamic coping mechanisms in a timely way. In addition, they support a bottom-up approach toe governance, bringing existing knowledge and endowments in rural communities to the forefront of smart and sustainable development solutions.

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