Cogent Food & Agriculture

ISSN: (Print) 2331-1932 (Online) Journal homepage: https://www.tandfonline.com/loi/oafa20

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To cite this article: Paula Antunes, Rui Santos, Inês Cosme, Anna Osann, Alfonso Calera, Dirk De Ketelaere, Anna Spiteri, Miguel Fernández Mejuto, Joaquín Andreu, Andrea Momblanch, Pasquale Nino, Silvia Vanino, Violeta Florian, Mihai Chitea, Cem Polat Çetinkaya, Meiry Sayuri Sakamoto, Milton Kampel, Luis Alberto Palacio Sanchez, Alaa El-din Abdin, Ravikumar Alanasiddaiah & Sashikumar Nagarajan | (2017) A holistic framework to assess the sustainability of irrigated agricultural systems, Cogent Food & Agriculture, 3:1, 1323542, DOI: 10.1080/23311932.2017.1323542

To link to this article: https://doi.org/10.1080/23311932.2017.1323542

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Cogent Food & Agriculture (2017), 3: 1323542

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Antunes et al., *Cogent Food & Agriculture* (2017), 3: 1323542
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A holistic framework to assess the sustainability of irrigated agricultural systems

Paula Antunes[1]*, Rui Santos[1], Inês Cosme[1], Anna Osann[2], Alfonso Calera[2], Dirk De Ketelaere[3], Anna Spiteri[3], Miguel Fernández Mejuto[4], Joaquín Andreu[5], Andrea Momblanch[5], Pasquale Nino[6], Silvia Vanino[6], Violeta Florian[7], Mihai Chitea[7], Cem Polat Çetinkaya[8], Meiry Sayuri Sakamoto[9], Milton Kampel[10], Luis Alberto Palacio Sanchez[11], Alaa El-din Abdin[12], Ravikumar Alanasiddaiah[13] and Sashikumar Nagarajan[13]

Received: 14 February 2017
Accepted: 24 April 2017
First Published: 03 May 2017

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Reviewing editor:
Fatih Yildiz, Middle East Technical University, Turkey

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Abstract: Irrigated agriculture is a key activity for the long-term survival of human-environmental systems and the assessment of agricultural sustainability has been gaining increasing relevance. In spite of several proposals developed, there is not a holistic approach that can be generally applied to assess sustainability of irrigated agricultural areas. In this paper we present a framework and associated indicators for the assessment of sustainability of irrigated agricultural systems in different contexts and locations. The framework covers four main sustainability dimensions: environmental integrity, economic resilience and profitability, social wellbeing and good governance. This approach was tested in 10 agricultural areas in eight different countries that represent a wide variety of situations in terms of agricultural development, environmental conditions, socio-economic settings and political contexts, but that share the fact that water use is a critical aspect for agricultural development. The obtained results illustrate the usefulness of the proposed framework to obtain a holistic picture of sustainability in irrigated agriculture areas, even in situations

Paula Antunes

ABOUT THE AUTHORS

Paula Antunes is professor at Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa and a researcher in CENSE – Center for Environmental and Sustainability Research. Her research interests focus in sustainability assessment, mapping and assessment of ecosystem services, environmental management and methods for participatory decision support in sustainability issues .

This work has been developed by a large team of co-authors in the scope of the EU FP7 SIRIUS project (Sustainable Irrigation water management and River-basin governance: Implementing User-driven Services). Rui Santos and Inês Cosme are researchers in the same institute. They have developed the sustainability assessment framework presented herein and coordinated the data collection process with the first author. Anna Osann and Alfonso Calera from Universidad de Castilla-La Mancha are the coordinators of SIRIUS. All authors share a common interest in the development of EO based products and services to support of sustainable irrigated agriculture.

PUBLIC INTEREST STATEMENT

Parallel to the acknowledgement of the critical role that irrigated agriculture plays in meeting the demand for food and fiber of a growing world population, there is significant evidence about its environmental and social impacts. The promotion of a more sustainable agriculture is pointed as a solution, but generally applicable tools to support the measurement of agricultural sustainability are still lacking.

We developed a framework to assess sustainability of irrigated agricultural systems in different contexts covering four main dimensions: environmental integrity, economic resilience and profitability, social wellbeing and good governance. This approach was tested in 10 areas in eight countries that represent a wide variety of situations in terms of agricultural development, environmental conditions, socio-economic settings and political contexts. The results illustrate its usefulness to get an overall picture of sustainability in irrigated agriculture areas and as a starting point for the construction of roadmaps of actions towards sustainability.

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of poor data availability. It is also an excellent starting point for the construction of roadmaps towards more sustainable agricultural systems.

Subjects: Agricultural Development; Environmental Sciences; Environmental Management; Environment & Society

Keywords: sustainability assessment; irrigated agriculture; indicators and framework; sustainable food production

1. Introduction

Agriculture is a key activity for the long-term sustainability of human-environmental systems. The concept of "multifunctional agriculture" acknowledges that agriculture provides a wide diversity of functions and benefits in addition to its primary role of producing food and fiber (Daugstad, Rønningen, & Skar, 2006; Renting et al., 2009; Van Huylenbroeck, Vandermeulen, Mettepenningen, & Verspecht, 2007). More recently, the role that agroecosystems can play in providing essential ecosystem services, such as regulation of soil fertility, water quality, carbon sequestration, support for biodiversity and cultural services has been emphasized (Dale & Polasky, 2007; Philip Robertson et al., 2014; Plieninger et al., 2012; Plieninger, Raymond, & Oteros-Rozas, 2016; Power, 2010; Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005). At the same time, agriculture can also be the source of numerous disservices, including loss of wildlife habitat, nutrient runoff, sedimentation of waterways, greenhouse gas emissions and contamination (Zhang, Ricketts, Kremen, Carney, & Swinton, 2007). In many regions, the expansion of agricultural land and the intensification of production methods are approaching their ecological, social and economic limits (Hani, Pintér, & Herren, 2008; Matson, 1997; Tilman, Cassman, Matson, Naylor, & Polasky, 2002).

In this context, agricultural sustainability has gained increasing relevance as a way to overcome these challenges and its assessment has become a principal endeavor for agricultural research, policy and practice (Van Cauwenbergh et al., 2007). Most definitions of sustainable agriculture are focused on the practices and technologies adopted (Pretty, 2008), referring to practices that are environmentally sound, economically profitable and socially just (Dale, Kline, Kaffka, & Langeveld, 2013). Sustainable agriculture must be capable of maintaining its productivity and usefulness to society indefinitely (Ikerd, 1993; Lewandowski, Härdtlein, & Kaltschmitt, 1999). Such an agriculture should use farming systems that conserve resources, protect the environment, produce efficiently, compete commercially, and enhance the quality of life for farmers and society overall.

A wide array of concepts that are somewhat related with sustainable agriculture has emerged recently (Petersen & Snapp, 2015; Pretty, 2008). Examples include organic farming (Rigby & Cáceres, 2001), sustainable intensification (Petersen & Snapp, 2015; Tilman et al., 2002), agroecology (Altieri, 2002), permaculture (Ferguson & Lovell, 2014; Suh, 2014) and conservation agriculture (Hobbs, Sayre, & Gupta, 2008; Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014). Some of these concepts are directly linked with one or two dimensions of sustainability,[1] while sustainable agriculture is more encompassing and holistic concept, albeit difficult to define.

The goal of agricultural sustainability is particularly difficult to achieve in intensive agricultural systems that are dependent on the input of one of the key resources for agricultural production: water. Irrigation has always played a central role in the development of agricultural systems in many parts of the world. Civilizations have risen and fallen with the growth and decline of their irrigation systems, while others have maintained sustainable irrigation for thousands of years (van Schilfgaarde, 1994). Parallel to the acknowledgement of the critical role that irrigated agriculture plays in meeting the demand for food and fiber of a growing world population, there is significant evidence about the environmental and social impacts of irrigated agriculture (Matson, 1997; Tilman et al., 2002). Even the economic sustainability of agricultural infrastructure projects is questioned in many cases.

Figure 1. Location of SIRIUS pilot areas.

In this paper we present a framework for the assessment of sustainability of irrigated agricultural systems that was developed in the scope of the EU FP7 SIRIUS project. SIRIUS (Sustainable Irrigation water management and River-basin governance: Implementing User-driven Services) aimed to stimulate the development of satellite assisted services for irrigation water management in agricultural regions under conditions of water scarcity and drought and for supporting water governance issues (e.g. trans-boundary water resources management, dealing with illegal water abstractions, multi-users and sectors). The application of SIRIUS was tested in 10 pilot areas in eight different countries (Figure 1) that represent a wide variety of situations in terms of agricultural development, environmental conditions, socio-economic settings and political contexts, but that share the fact that water use is a critical aspect for the sustainability of agriculture.

In the following sections, we review different approaches and frameworks that have been developed to assess the sustainability of agricultural systems and describe the SIRIUS framework, stressing the main contributions in relation to existing approaches. We then present the results that we obtained from the application of this framework in the pilot areas and derive lessons in terms of pathways for sustainable agriculture and suitability of the suggested framework.

2. The challenge of measuring agricultural sustainability

Agricultural sustainability is not only a difficult concept to define (Hayati, Ranjbar, & Karami, 2010), but also is difficult to implement, measure and monitor (Binder, Feola, & Steinberger, 2010; Farshad & Zinck, 1993; Hayati et al., 2010; Rao & Rogers, 2006). Several approaches to guide the assessment of agricultural sustainability have been proposed in the literature, relying usually on the definition of a set of sustainability criteria and associated indicators, organized around a conceptual or operational framework, generally structured following a hierarchy (de Olde, Oudshoorn, Sørensen, Bokkers, & de Boer, 2016). These methods differ in terms of their purpose, scope for assessment, underlying sustainability concepts, dimensions and indicators covered and development approach. In Table 1 we present an overview of some of these proposals, distinguishing their focus, coverage of sustainability dimensions and methodological approach followed for assessment and integration.

Many of the frameworks and approaches identified have been guided by local priorities and practices and only limited attempts at developing systematic, widely applicable frameworks are reported, as has already been noted in Rao and Rogers (2006). Most of the approaches that have been

Table 1. Approaches for assessing agricultural sustainability

Approach/framework	Focus	Sustainability dimensions covered (number of indicators)				Methodological approach
		Environmental	Economic	Social	Governance	
Sustainable rural livelihoods (SRL, Scoones, 1998)	Link between livelihoods and natural resource use Farming systems in rural areas in sub-Saharan Africa	Indicators organized around 5 capital stocks (natural, physical, financial, human and social)				List of indicators identified combining top-down and bottom-up approach
Rigby et al. (2001)	Farm level based on input use and agricultural practices—focus on organic agriculture	5				Aggregate indicator based sum of scores of the impact of practices on a scale from 0 to 3
Zhen and Routray (2003)	Farming practices in developing countries	7	4	4		Criteria for selection of indicators and proposed set of operational indicators
Rasul and Thapa (2004)	Farming systems, developed for Bangladesh	5	3	4		Analysis of individual indicators
Water vulnerability index (Sullivan, 2011; Sullivan & Meigh, 2005)	Assessment of water vulnerability of municipalities in a river basin	9	4	3		Composite index combining supply driven and demand driven water vulnerability
Response-inducing sustainability evaluation (RISE, Häni et al., 2003, 2006)	Farm level assessment	7	3	2		RISE sustainability polygon. Indicators are evaluated combining state and driving force parameters
Indicateurs de durabilité des exploitations agricoles (IDEA, Zahm et al., 2006)	Farm level sustainability assessment	19	6	15		Scoring system that awards points to indicators in the 3 sustainability dimensions Aggregated score corresponds to lowest value
Rao and Rogers (2006)	General framework for assessing sustainability at different scales	16 indicators organized into: agroecosystems, stress, vulnerability and management				DPSIR based Agricultural sustainability index
Sustainability assessment of farming and the environment (SAFE, Van Cauwenbergh et al., 2007)	May be applied at 3 spatial levels: parcel level, farm level and landscape/region Focus on on-farm activities	22	10	21		Hierarchical framework of principles, criteria and indicators
Castoldi and Bechini (2010)	Cropping systems	9	3			Index value based on weighted average
Gómez-Limón and Sanchez-Fernandez (2010)	Farm level assessment Applied to study rain-fed and irrigated agriculture	9	3	4		Composite indicator calculated using different weighting and aggregation methods
Sustainability assessment of food and agriculture systems (SAFA, FAO, 2013a, 2013b)	Sustainability in the value chain—focus on companies	6	4	6	5	Detailed guidance for application; 5 points rating scale
SOSTARE—analysis of farm technical efficiency and impacts on environmental and economic sustainability (Paracchini et al., 2015)	Farm level assessment of sustainability of management practices considering environmental and economic pillars To be used by farmers, technical advisors and policy makers	22 + 6	9			In environmental we have considered the indicators included in the agronomic dimension (22) and in the ecological dimension (6) Aggregation of indicators using a compensatory approach within each dimension and non-compensatory among the three dimensions

suggested focus on the assessment of agricultural practices at farm level (e.g. farming practices and farming systems), cropping systems, agricultural organizations (e.g. agri-businesses), or the food value chain. Methods aiming to assess sustainability at the landscape/region/watershed scale are not so common (Dale et al., 2013).

Some of the proposals are more targeted to environmental concerns and agricultural management practices (Castoldi & Bechini, 2010; Rigby, Woodhouse, Young, & Burton, 2001), while others (FAO, 2013a; Zahm, Viaux, Girardin, Vilain, & Mouchet, 2006) try to cover more sustainability dimensions combining environmental with economic and/or social aspects. Governance aspects are absent in most of the reviewed methods, with the exception of the SAFA (FAO, 2013b) and Sustainable Rural Livelihoods (Scoones, 1998; Woodhouse, Howlett, & Rigby, 2000) frameworks. The last one acknowledges explicitly the linkage between the wider economic, institutional and policy context as part of the analysis of strategies of natural resource management.

Some authors use sustainability polygons/webs to represent graphically the sustainability of systems along the dimensions considered, while others rely on the calculation of an aggregate indicator/composite index. Displaying individual indicator scores separately avoids having to aggregate across different incommensurable scales/dimensions and is more compatible with a strong sustainability approach (Gómez-Limón & Sanchez-Fernandez, 2010; Martinez-Alier, Munda, & O'Neill, 1998). On the other hand, it does not allow the direct comparison of cases/farming systems, or the establishment of sustainability rankings and the results are more difficult to interpret and communicate. In the end, the approach to aggregation of indicators depends largely on the objectives of the sustainability evaluation exercise.

In the scope of SIRIUS there was a need to assess the sustainability of irrigated agricultural areas in a holistic perspective, in order to support the development of roadmaps for action at different levels towards a sustainable future. We also wanted to identify key entry points to stimulate the uptake of SIRIUS products and services in farming systems. Although the different approaches reviewed contain elements that are useful for these purposes, there was no single approach that could be directly transferred. As stated, most of the existing frameworks do not cover all sustainability dimensions in a comprehensive and balanced way and/or are not focused on the irrigation perimeter/watershed scale. Water management, which is a central issue in irrigated agriculture, is fully addressed only in the Water Vulnerability Index (Sullivan & Meigh, 2005), which, on the other hand does not cover other sustainability aspects. These constraints have motivated the proposal for a new framework for assessing the sustainability of irrigated agricultural systems at the scale of an agricultural area/irrigation perimeter.

3. A framework for sustainability assessment of irrigated agricultural systems

3.1. Purpose and framework development process

The main purpose of the SIRIUS sustainability assessment framework is to provide a holistic understanding and represent the "big picture" regarding sustainability of irrigated agricultural areas in order to support the formulation of sustainability strategies. The main objective is to understand the major issues related to the environmental, economic and social dimensions of sustainability of agricultural systems and associated governance requirements. This framework is to be used to support the identification of strong points and opportunities for improvement, as well as the development of roadmaps of actions to promote sustainability of agricultural systems.

The SIRIUS framework was designed to be of quite general application, meaning that it may be used to assess sustainability of irrigated agricultural systems in different parts of the world and in very different contexts, ranging from highly sophisticated, intensive and technology-based irrigation systems, to more traditional and family-based agro-systems.

We adopted a transdisciplinary approach (Binder et al., 2010) to the development of the framework in which we combined a theory-based definition of sustainability with the input from relevant stakeholders. We took as a starting point the definition of J. Ehrenfeld that sustainability is the "possibility that humans and other life will flourish on the Earth forever" (Ehrenfeld, 2008) and we have worked towards the identification of the basic conditions necessary to ensure this possibility in irrigated agricultural systems. In line with what is suggested by Pretty (2008), our approach to agricultural sustainability incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods), and addresses wider environmental, economic and social conditions as well as the associated governance systems to achieve these two aims. We have used some elements of other approaches, such as the framework for socio-economic assessment of irrigated agricultural systems developed by Santos, Antunes, and Beça (2008), the lessons from the multi-criteria analysis of irrigated agricultural systems presented in Antunes, Karadzic, Santos, Beça, and Osann (2011) and the Climate Vulnerability Index and Water Vulnerability Index (Sullivan, 2011; Sullivan & Meigh, 2005). The dimensions and core components considered in the SAFA framework (FAO, 2013a) were also used as a basis to define some elements of this framework.

In order to identify important aspects to be included in the framework, we organized a participatory workshop with members of SIRIUS regional teams that included researchers, water users and water managers (e.g. members of regional agricultural/water bodies, water users associations) from the 10 pilot areas, in a total of 29 people. We organized the participants in groups of 2–4 elements according to their area of origin and asked them to discuss whether they considered their area, and the agricultural activity developed therein, to be sustainable. Each group had to identify the arguments pro and against the claim for sustainability in their pilot area. The groups had to report back to the plenary and there was a joint discussion around the main issues that were identified. From the inputs of the different areas, we extracted a list of key sustainability aspects to be included in the framework. Given the diversity of geographical, cultural and agricultural contexts covered by SIRIUS pilot areas, we ensured this way the coverage of concerns from different perspectives. This process was fundamental to adjust and complement the list of issues that had been previously identified based on literature. In this way, we combined a top-down and a bottom-up approach in the framework development process.

The SIRIUS framework is to be applied to assess sustainability of irrigated agricultural systems in very different countries and contexts, at the irrigation perimeter/watershed scale, and therefore one important concern was its suitability to be applied in contexts of reduced availability of baseline information. Many of the indicators used to measure sustainability "are not particularly useful to farmers/water managers or are too time-consuming to measure on a regular basis" (de Olde et al., 2016; Norman, Janke, Freyenberger, Schurle, & Kok, 1997). Taking this into account, the associated burden of data collection was considered in the selection the indicators to be included.

The SIRIUS framework was conceived and tested for application in irrigation perimeters. However, it may also be applied at other spatial levels, such as the farm level, landscape level, the hydrological region (river basin level), or even at the national level.

3.2. Main elements of the framework

The SIRIUS framework considers four basic dimensions in sustainability assessment of irrigated agricultural areas: (1) environmental integrity; (2) economic profitability and resilience; (3) social well-being and (4) good governance. For each dimension a set of core issues were identified, to which aspects to be evaluated and corresponding indicators are associated. Figure 2 summarizes the four dimensions and core issues of the SIRIUS framework.

Table 2 details the aspects to be evaluated in each core issue and suggested indicators to be used in the assessment. Not all indicators listed in Table 2 are primary indicators (i.e. that can be directly measured). Some of them are indices or composite indicators that result from the combination of

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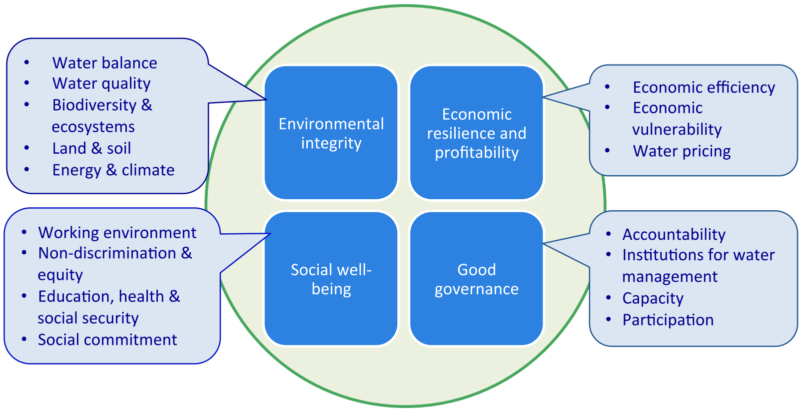
Figure 2. SIRIUS framework for sustainability assessment: main dimensions and core issues.



several indicators/variables. We use here the term indicator to refer to all measurable variables that are used to evaluate the sustainability performance of an irrigation perimeter in each core issue, as used in the SAFA system (FAO, 2013a). Some of the indicators refer to variables for which quantitative data are available or that can be measured in an objective way (e.g. water productivity in agriculture), while others refer to the assessment of subjective aspects and perceptions (e.g. sense of community). In these cases, and in the absence of data, we recommend the collection of information from expert opinion or stakeholder consultation (see Section 3.3). Note that the indicators list that is provided herein is illustrative and may be adjusted for application in different contexts.

3.2.1. Environmental integrity

The environmental integrity dimension encompasses the evaluation of the integrity of the natural capital of irrigated agricultural areas, and its capacity to ensure the fulfillment of the basic ecological functions underpinning the delivery of a sustainable flow of ecosystem services.

Since the framework is particularly targeted towards irrigated agricultural systems, the sustainability of water use patterns is a major aspect to consider in this dimension. The definition of aspects and indicators used in this core issue was based on the Water Vulnerability Index (Sullivan, 2011).

Water balance is evaluated considering the availability of water resources, their variability and the patterns of water consumption and use in the area. Water productivity is a key aspect for determining sustainability of irrigated agricultural systems. Water productivity is generally defined as the ratio of the net benefits obtained from agricultural system to the amount of water required to produce those benefits (Molden et al., 2007). In this dimension, we are particularly concerned with the physical water productivity that relates the mass of agricultural output to the amount of water used. The results obtained for this indicator are compared with the reference values considered in the Water Footprint Network (WFN) database for the main crops in the corresponding region (Mekonnen & Hoekstra, 2011). The water footprint (Hoekstra & Chapagain, 2007) of the cultivated crops and the virtual water balance (Allan, 1998; Hoekstra & Hung, 2005) for the area are very useful and powerful indicators in this dimension, but they may be difficult to operationalize in many cases.

Water productivity in agriculture can be improved through different pathways that include small-scale water management practices, deficit irrigation, modern irrigation technologies and soil water conservation measures (Ali & Talukder, 2008; Molden et al., 2007). The identification of the most suited strategy (or combination of strategies) in each case is very context dependent and can only be realized taking an integrated and locally adjusted perspective (Molden et al., 2010).

The quality of water resources is measured by the ratio of water bodies classified as having poor or bad quality, according to the local water quality standards, and also by the evaluation of existing cases of constraints to agricultural water use due to poor quality.

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Table 2. SIRIUS framework for sustainability assessment—aspects and indicators

Core issues	Aspects	Indicators
Environmental integrity		
Water balance	Water availability	Available resources
		Mean annual run-off
		Annual groundwater recharge
		Main source of water for irrigation
		Water storage capacity
	Variability of water resources	Number of days per year/during growing season with precipitation above 1 mm
	Water consumption and use	Annual water consumption
		Distribution of consumption (agriculture, domestic) and expected trends
		Average duration of irrigation campaign
		(Physical) Water productivity in agriculture (ton m^{-3} water used)
		Share of population domestic water supply
		Share of population with wastewater drainage and treatment
		Share of water reused
		Virtual water balance (water footprint components) (if data available)
Water quality	Water quality	Share of water resources with poor or bad quality
		Irrigation constraints from poor water quality
Biodiversity and ecosystems	Biodiversity enhancement farming systems	Share of cultivated land with biodiversity enhancement measures
Land and soil	Soil structure	Share of soil with poor structure
	Salinization of soils	Share of salinized soils
	Soil quality (chemical)	Share of soil with contamination (e.g. pesticides)
	Land degradation	Share of area with high erosion risk
Energy and climate	Climate change	Energy consumption and intensity
		Carbon footprint of agriculture
		Vulnerability to climate change
Economic resilience and profitability		
Economic efficiency	Revenues and costs	Annual crop yield and value of production
		Total costs of production
		Costs of water and energy inputs
		Crop gross value added (GVA) in agriculture
		Investment payback period
		(Economic) Water productivity in agriculture ($ m^{-3} water used)
Economic vulnerability	Household vulnerability	Share of economically vulnerable households
	Water dependency	Share of irrigated land in total cultivated land
		Share of employment in water dependent sectors
		Share of GVA in water dependent sectors
	Self-reliance	Investment in relation to depreciation
		Ratio of public to private investment
		Subsidies on investment
		Revenue/Total O&M costs for irrigation
		Maximum capacity to pay for water
		Share of subsidized area on total irrigated area
		Value of subsidies for production
	Adoption of risk minimization strategies	Diversification of cultures, seed supply and financial resources

(*Continued*)

Table 2. (*Continued*)

Core issues	Aspects	Indicators
Water pricing	Water tariffs and taxes	Tariff structure (volume/area based)
		Value of water tariffs
		Other taxes on water
Social well-being		
Working environment	Wages	Average salary in agriculture compared with regional average
	Working conditions	Assessment of working conditions
	Working hours	Average working time in agriculture
Non-discrimination and equity	Gender equality	Wage difference between genders
	Reduction of discrimination and inequalities	Perceived fairness regarding opportunities and income distribution
Education, health and social security	Educational level of population	Adult literacy rate
		Qualification of agricultural workforce
	Medical care	Access to medical care
	Social security	Share of population covered with social security
Population dynamics and social interactions	Population dynamics	Age structure of population
		Migration trends
	Social commitment	Sense of community and community relations
		Engagement in civil society organizations
Good governance		
Accountability	Commitment	Degree of commitment to respond to and balance the needs of stakeholders in decision-making
		Mechanisms to monitor the implementation of policy processes and decisions
Institutions for water management	Rule of law	Adherence to rules-based approaches
		Enforcement capacity
	Conflict management and water allocation	Formal and informal institutions for conflict resolution
		Perceived fairness of water allocation rules
Capacity	Water governance capacity	Technical water governance capacity
		Financial capacity of water management organizations
		Technical capacity of farmers/landholders
Participation	Public participation in water resources management	Degree of participation in decision-making

The contribution of agricultural areas to biodiversity conservation is assessed by the percentage of cultivated land that is managed adopting biodiversity enhancement practices, such as EU Common Agricultural Policy (CAP) agro-environmental measures (Burton & Paragahawewa, 2011; Kleijn et al., 2006), biodiversity certification systems (Tscharntke et al., 2015) or payments for ecosystem services schemes (Engel, Pagiola, & Wunder, 2008; FAO, 2011; Wunder, 2015).

The maintenance of soil quality is critical to environmental sustainability (Arshad & Martin, 2002), but pressures such as poor fertilizer and water management, soil erosion and shortened fallow periods have led to a growing human-induced soil degradation and loss of productivity (Tilman et al., 2002). Land degradation and soil quality are measured in SIRIUS by the share of soils with poor structure (physical soil quality), degree of soil salinization, share of soils with contamination (chemical quality) and areas under high erosion risks.

Agriculture depends directly on climatic conditions and will be influenced by climate change. On the other hand, agricultural activities use natural resources, in particular energy, and have an impact on climate change (Underwood et al., 2013). Climate change and energy issues are accounted considering two broad concerns: (1) vulnerability to climate change and corresponding adaptation plans; and (2) energy intensity of agriculture in the area, with the associated carbon footprint.

Climate change may affect crop productivity through changes in the growing season of crops, the timing of the crop cycle, water availability and irrigation requirements and the increasing frequency and unpredictability of extreme events such as floods and droughts (Calzadilla et al., 2013; Nelson et al., 2009). The direction and magnitude of the expected impacts of these changes in agricultural production in different parts of the world is variable and uncertain. Vulnerability to climate change is an important aspect for the sustainability of agriculture and there has been a growing recognition of the need to develop adaptation measures in face of the expected climate change scenarios (Howden et al., 2007). This is measured in SIRIUS using a 5-point Likert scale, from very low to very high vulnerability. Users are asked to classify the vulnerability of their area in this scale and document the sources of information (e.g. climate change impact assessments, adaptation plans) that ground their score.

Agriculture is an important source of greenhouse gas (GHG) emissions worldwide (Vermeulen, Campbell, & Ingram, 2012). The use of fossil fuels in agricultural machinery and irrigation systems can be an important source of GHG emissions in irrigated agriculture. The indicator energy intensity of agriculture refers mainly to direct energy consumption, comprising the use of energy in field and farm operations (e.g. water pumping). Indirect energy consumption, i.e. energy consumed to produce inputs (e.g. fertilizers) should also be considered, but it is more difficult to assess. Ideally the carbon footprint (Pandey, Agrawal, & Pandey, 2011; Wiedmann & Minx, 2007) of agricultural activities in the study area taking a life-cycle perspective should be calculated, but this indicator may be difficult to calculate in practice and therefore is not considered in the assessment in these cases.

3.2.2. Economic resilience and profitability
The economic dimension of sustainability is assessed considering three main issues: economic efficiency, economic vulnerability and water pricing. Economic efficiency deals mainly with the production capacity of the agro-system and the value it generates for farmers. Besides the standard economic indicators used in this domain, a particular focus is placed in the assessment of water and energy costs and in the calculation of the economic water productivity in agriculture, i.e. the economic benefits obtained per unit of water used (Molden et al., 2007, 2010).

Economic vulnerability encompasses the evaluation of key aspects that reflect how vulnerable the agricultural system is to macroeconomic fluctuations, food market conditions, market power of key actors, financial markets crisis, significant environmental changes or to social and political instability (Briguglio, Cordina, Farrugia, & Vella, 2009; Varela-Ortega, Esteve, Downing, & Bharwani, 2009). Economic vulnerability is related with the capacity to accommodate the impact of these factors in farm income and with the risk that the minimum income that will allow farmers to continue operating will not be achieved. Vulnerability is measured in SIRIUS by the share of economically vulnerable households in the community, the level of subsidy dependence in agriculture, the water reliance of main cultures, the capacity to pay for water and the capacity to use diversification as a strategy to reduce risks (e.g. crops, seeds, financial resources).

Since all SIRIUS pilot areas share the fact that water use is a critical aspect for agricultural development, a particular attention is focused on water pricing as a key economic instrument for water management (Johansson, 2002; Molle, 2009). This includes an analysis of tariffs applied on water services (water tariffs), including their structure and unit values, as well as of other water taxes (e.g. taxes on water abstraction for agriculture) that provide relevant incentives for decisions on water allocation and use.

3.2.3. Social well-being
Similarly to the approach followed in the Sustainable Rural Livelihoods (SRL) framework (Scoones, 1998) and in the SAFA system (FAO, 2013b), the evaluation of social sustainability is centered in the

assessment of the assets and conditions to fulfill basic human needs, such as means of living, health and safety, working conditions, as well as the means to satisfy aspirations for a better life, such as education and non-discrimination. Strong social relations and population dynamics are also essential elements of social sustainability of agricultural systems.

The living and working conditions of farmers are an essential element of social sustainability (Källström & Ljung, 2005). In the SIRIUS framework, this accounted by the comparison of wages in agriculture with those in other activity sectors, by the assessment of working conditions for agricultural laborers and by the amount of working hours in agriculture. Non-discrimination and equity are also important issues that are evaluated in terms of gender equity and of the distribution of opportunities and income in society. Issues such as reliance on child labor and other aspects that may be particularly relevant for some areas can be added to the framework in this dimension.

Education and qualification of agricultural workforce, access to medical care and degree of coverage with social security, unemployment and retirement pensions represent basic assets to ensure sustainable livelihoods in agricultural areas.

Population dynamics is assessed by the analysis of the main demographic trends in the area and the age structure of rural populations. The degree of social interaction in the population is measured by perceptions regarding sense of community and the engagement of local population in civil society organizations.

3.2.4. Good governance

Environmental governance refers to the set of regulatory processes, mechanisms and organizations through which political actors influence environmental actions and outcomes (Lemos & Agrawal, 2006). Governance is measured considering four main aspects: accountability, institutions for water management, capacity and participation, that are directly linked with the Good Governance Principles established by the United Nations Development Program (1997, 2014).

Sustainable development will require that public officials account for actions taken in the public's name and with public resources (UNDP, 2014). Accountability measures the degree of commitment of responsible authorities to respond to and balance the needs of stakeholders in policy and other decision-making processes, as well as the strength of the existing formal and informal mechanisms to monitor the implementation of policy processes. Transparency and responsibility are also important elements in this regard (Lockwood, Davidson, Curtis, Stratford, & Griffith, 2010).

Effective rule of law is also a basic principle in governance for sustainable development (Rogers, Hall, Van de Meene, Brown, & Farrelly, 2003). The degree of adherence to rules and the law enforcement by resource managers are evaluated in the institutions for water management aspect. Here we also consider the perceived fairness of water allocation rules and the existence of (formal or informal) institutions to handle conflicts over the allocation of resources.

Capability refers to the systems, plans, resources, skills, leadership, knowledge, and experiences that enable organizations, and the individuals who work for them, to effectively deliver on their responsibilities (Lockwood et al., 2010). Sustainable agriculture requires technical capacity from both authorities and farmers/landowners to ensure sustainable management of resources. On the other hand, it also requires financial capacity of water management organizations to ensure basic activities such as monitoring, auditing, information management and compliance control.

Participation is a key element in governance for sustainable development contributing to improve the quality and legitimacy of decisions and to build capacity of all involved in the processes (National Research Council, 2008; Renn, 2006; Renn & Schweizer, 2009). The use of participatory approaches has been advocated on grounds of justice and democracy in procedure and an appreciation that complex, multidimensional issues, such as the ones involved in sustainable agriculture and water management cannot be effectively handled on a purely technocratic basis (Antunes, Kallis, Videira, & Santos, 2009; De Marchi & Ravetz, 1999; Pahl-Wostl, Mostert, & Tàbara, 2008). In the SIRIUS framework the degree of participation in decision-making is evaluated by placing existing practices along the spectrum for public participation proposed by the International Association of Public Participation (IAP2)[2] that includes 5 levels of involvement: information, consultation, involvement, collaboration and empowerment, inspired by the public participation ladder (Arnstein, 1969).

3.3. Reference values and data collection

The concept of agricultural sustainability is relative and case dependent (Pretty, 2008), as it depends on the particular environmental, cultural and social context of each case/area. Furthermore, sustainability is not an absolute condition of an agricultural system, but more seen as an evolving concept. What is considered "sustainable" or "unsustainable" depends very much on local conditions and recent trends (Zhen & Routray, 2003). For this reason, the SIRIUS framework does not have underlying sustainability target values and does not explicitly include absolute reference values for the suggested indicators. Relative reference values, which compare indicators values with an initial value, a regional average or a desirable trend for that particular context (de Olde et al., 2016), are used instead.

For those indicators where there exists a sound basis for establishing locally adjusted reference values, they should be used in the assessment. For example, we suggest the comparison of obtained water productivity values for the main crops with the reference values used by the Water Footprint Network (Mekonnen & Hoekstra, 2011) to support water footprint calculations. Also, for instance, local water quality standards should be used to assess the share of water bodies with poor quality.

Being so, the results obtained through the application of this framework should not be used to derive a single measure of sustainability of an area, to rank different areas or to establish sustainability ratings of agricultural systems. The idea is to support the development of change processes leading to agricultural sustainability (Rigby & Cáceres, 2001) rather than to prescribe a set of practices or absolute targets.

Information used to support the application of the SIRIUS framework in a given area should be obtained from officially published data (e.g. official statistics) or other verifiable sources (e.g. scientific literature) whenever possible. This should be complemented with tailored data collection and qualitative assessments when necessary. When needed, data should be collected at the scale that is most relevant to understand the issue at hand (for example data on costs and revenues should be collected at the farm/field level). The focus of analysis of the SIRIUS framework is at the irrigation perimeter/regional level, and therefore indicators should be reported at this scale.

Many of the indicators used in the social wellbeing and good governance dimensions reflect stakeholders' perceptions regarding each issue (e.g. perceived fairness of water allocation rules). In these cases, we use a 5-point Likert scale to express the assessment (e.g. very good, good, fair, poor, very poor) and recommend that information should be collected with a wider involvement of relevant actors, either through the organization of public opinion polls, targeted surveys or the organization of participatory events such as focus groups.

4. Application: sustainability assessment in SIRIUS pilot areas

To test the usefulness of the framework and its capacity to be applied in different contexts we used it to assess the sustainability of 10 irrigated agricultural areas in 8 different countries, corresponding to the pilot areas in the SIRIUS project.

A questionnaire was developed to support the data gathering process in the pilot areas (available as supplementary material to this paper). This questionnaire was distributed to leaders of regional teams that took the responsibility of collecting the relevant information in appropriate sources in each area. Meetings and interviews with relevant stakeholders in each pilot area played a very relevant role to support data collection and to validate the information.

Table 3 synthesizes the main results obtained for the 10 pilot areas. A more detailed version of this Table is presented as supplementary material and a full account of the obtained results is provided in (Antunes, Santos, & Cosme, 2013). The interpretation of the results obtained should be performed with caution and take into consideration the difficulties in obtaining the underlying data that were present in all areas.

For each pilot area, a "sustainability profile" was prepared (Figure 3). This profile depicts the score in a 0–5 scale that was attributed to each of the core issues of the framework, based on the values obtained for the different indicators. Since there are no absolute reference values, we did not use a mathematical aggregation rule to calculate this score, but performed a classification of the values obtained, considering local standards and reference values as explained in Section 3.3.

The radar plots are very useful to summarize results, to understand the main sustainability challenges and to identify opportunities for improvement in each pilot area. However, they should not be used to support a comparison across areas, since there are no absolute reference values and many of the indicators used in the framework (in particular social and governance issues) are very context dependent. Their interpretation should be accompanied by the narrative description provided in Table 3 and by the analysis of the results obtained for the different indicators. Nevertheless, it is possible to derive some common lessons.

Environmental integrity is an underlying basic pillar for sustainability. Even in areas with an overall good performance across all dimensions, poor performance in one aspect of environmental integrity (e.g. water availability or soil quality) can be a limiting factor for sustainability. In irrigated agricultural areas, it is particularly relevant to develop plans to ensure sustainable provision of water with good quality in the future and to balance current and future needs of the different uses within the carrying capacity of the environmental system.

Water scarcity and water quality are the most critical issues in this dimension. There is still a large room for improvement of agricultural water productivity in all studied areas, showing that the development of technologies and capabilities to enhance water (and nutrients) management is an essential element of sustainability roadmaps in very different contexts, ranging from the more sophisticated intensive systems (e.g. Spanish and Italian pilot areas) to less developed (e.g. India pilot area) agricultural systems.

Vulnerability to climate change is a key aspect in all pilot areas and it is important to develop and implement adaptation plans to ensure resilience of irrigated agriculture areas under climate change scenarios.

Agriculture is very relevant for the regional economy in the studied areas, but profitability is generally reported as low and dependent on a limited number of cultures and on the availability of water. Tailored water pricing schemes are an essential element of the policy toolbox to provide incentives for water saving, increasing water productivity and managing water scarcity in an efficient way. This aspect is still poorly developed in the areas considered in our study: in some of them (e.g. Brazil and Egypt) water is not paid; others (e.g. Italy, Turkey) have implemented area-based tariffs, which provide no incentive for water saving and finally, those that have volume-based schemes in place (e.g. Spain and Mexico) refer that these need to be adjusted to provide adjusted and effective incentives. In all cases, it is important to consider affordability as a criterion in the design and implementation of water pricing mechanisms, balancing water costs and farmers' capacity to pay for water.

The dependence upon public subsidies is common to almost all studied areas, and in many agricultural areas around the world. In this context, conditioning the granting of public subsidies to the

Table 3. Results of sustainability assessment in pilot areas

Pilot area	Description	Environmental integrity	Economic resilience and profitability	Social well-being	Good governance
Mancha Oriental (Spain)	Located in the Jucar River Basin, in the East of Iberian Peninsula. Large farms predominate. Almost all farms are integrated into a large irrigation community (Junta Central de Regantes de la Mancha Oriental). The main crops are wheat/barley, vineyard, maize and alfalfa. Problems typical of semiarid zones with an intensive surface and (mostly) groundwater use, water scarcity and frequent droughts. Political and social disputes are originated by water resources allocation between different uses and areas, upstream and down-stream. Groundwater overexploitation has reverted the aquifer-river relationship	Water scarcity and the large dependency of the economy and social fabric upon irrigated agriculture are the main sustainability challenges. This threat may become even more serious in a scenario of climate change, due to the high vulnerability. Water productivity for some crops may be improved. Energy intensity of agriculture is high	Agriculture is very relevant for the regional economy; it is profitable and mainly market-oriented. Public subsidies are important. Invest-ment in agriculture is increasing mainly in irrigation and marketable crops. The existing volume-based water pricing scheme may be adjusted to provide stron-ger incentives to water efficiency. Water costs and price are relevant aspects for the competitiveness of this area	Social wellbeing is overall good. The main problems are related with the still unequal distribution of opportunities and income and with the tendency for a shrinking population	Institutions are capable of promoting water resources management and rules are perceived as fair. River Basin Management Plans have been established. The water users' associations allocate and manage water to guarantee access by end users
Marina Baja (Spain)	Located in the Jucar River Basin District, in the Alicante Province. There are mainly very small farms, organized in several irrigation communities The main crops are almond tree, olive tree, citrus and medlar Problems related to water scarcity and large proportion of domestic water demands (with high influence of tourism) with high reliability supply requirements	The main sustainability challenges are related with the relative scarcity of water resources, despite the already existing diversification of sources through desalination and water reuse. This problem may become even more serious in a scenario of climate change, due to the high vulnerability Energy intensity of agriculture is high	Agriculture is relevant for the regional economy and it is profitable and mainly market-oriented. Public subsidies are not relevant and investment in agriculture is stagnant. Water and energy costs are relevant. The existing volume-based water pricing scheme could provide stronger incentives to water efficiency. Water availability, costs and price are relevant aspects for agricultural competitiveness	Social wellbeing is overall good. The main problems are related with the still unequal distribution of opportunities and income and the tendency for a shrinking population	Institutions are capable of promoting water resources management and rules are perceived as fair. Water users' associations manage water allocation to guarantee water access by end users

(*Continued*)

Table 3. (*Continued*)

Pilot area	Description	Environmental integrity	Economic resilience and profitability	Social well-being	Good governance
Consorzio di Bonifica Sannio Alifano (Italy)	Located in Southern Italy, North of the Campania Region. The Consortium manages water allocation in agriculture. Water for irrigation comes mostly from the Volturno and Lete rivers The farms are characterized by the prevalence of the micro property and dispersion of parcels. The main crops are green maize, forage, orchard, olive and vineyard. The main challenges are related with water misuses and competition between activity sectors. Agriculture uses between 50 and 70% of the total freshwater	The area is highly dependent on agriculture (particularly maize), which is highly dependent on irrigation. Management of water resources is key for sustainable development. Water quality is the most worrisome issue. The adoption of measures to control pressures on water quality is a priority, alongside with improvement in water use efficiency	Agriculture is relevant for the regional economy, although it is not very profitable and depends on a limited number of cultures. It is market oriented although highly dependent on public subsidies. The economic productivity of water is very high for some crops but much lower for others. The existing area-based water pricing scheme does not provide a strong incentive to improve water productivity	Social wellbeing is overall perceived as good. The most relevant concern is the perceived lack of opportunities for farmers, which leads to abandonment of agricultural activities, emigration and shrinking population	Increase in accountability and financial capacity of water management institutions seem to be the main governance concerns. Direct involvement of farmers in decision-making processes should increase, since participation now takes place mainly through representative delegation
Terasa Brăilei/ Cazasu (Romania)	Cazasu is part of the Terasa Brăilei Nord scheme. Water for irrigation comes from the Danube river. Adjustments in private property rights led to fragmentation of agricultural land, with very small family farms and large farms with legal status. The main crops are: maize, wheat, lucerne, sugar beet, sunflower, vegetables and other crops. The local state authority (National Agency for Land Reclamation—Braila branch) manages water pumping from the Danube. The 6 Water Users Associations contract with NALR water for irrigation and manage their own infrastructure	Agriculture is highly dependent on irrigation from surface water. This source is reliable and water scarcity is not a constraint. However, poor water quality is a serious concern. Energy intensity of agriculture is high, since all water is pumped from the river	Agriculture is very relevant for the regional economy and is profitable, although with variations. Crops cultivated for seeds are more profitable. Investment in agriculture is increasing, but agriculture is highly dependent on public subsidies. The economic productivity of water is much higher for maize seeds than for other crops. Water energy costs are relevant in the cost structure. The existing volume and area based water pricing scheme needs to be adjusted to promote water efficiency, considering farmers' capacity to pay	The working conditions and distribution of opportunities and income are perceived as fair. There is a high rate of adult literacy and agricultural workers are qualified, but access to medical care and social security is still poor. The age pyramid corresponds to a shrinking population, despite immigration trends	Accountability of local authorities is low and relations with stakeholders are poor. Water allocation is seen as unfair, since rules tend to favor large farms. Authorities have a weak capacity to promote rules' enforcement and there are no formal institutions for conflict management. Water management authorities are seen as having poor technical and financial capacity and participation is limited

(*Continued*)

Table 3. (*Continued*)

Pilot area	Description	Environmental integrity	Economic resilience and profitability	Social well-being	Good governance
Gediz Irrigation (Turkey)	Located in western Anatolia in the Aegean region, neighboring the city of Izmir. The Gediz Irrigation Association scheme is integrated in this basin	Water scarcity and degradation of water quality are the main environmental challenges in Gediz Irrigation area. The balancing of agricultural activity with biodiversity conservation does not seem to be a policy priority	Agriculture is an important economic activity but it depends on a limited number of cultures. There are no data on agricultural profitability, but the area is highly dependent on public subsidies, namely for maize and cotton. Water and energy costs are very relevant, especially on fields using groundwater. The existing area-based water pricing scheme does not promote water use efficiency	Working conditions are poor: most of the workforce is composed of seasonal workers that do not have adequate conditions. Unfair distribution of opportunities and income is also a problem. Although overall coverage with health and education is good, agricultural workers still have poor access to medical care and are poorly qualified (primary education)	There is adequate institutional capacity to promote water resources management and the rules for water management are perceived as clear and fair. A more direct involvement of farmers in decision-making processes in would be desirable
	The main crops are maize, vineyard, tomato and cotton	Main crops are very dependent on water and agriculture is vulnerable to climate change			
	The major conflict in the basin is the competition among water users due to water scarcity, water pollution and mainly water allocation deficiencies by national authorities				
Morada Nova (Brazil)	Contained in the sub-basin of the river Banabuiú that comprises the central hinterland of Ceará state more strongly subject to drought	Agriculture in is highly dependent on irrigation that is supplied from surface water source that is considered reliable, but vulnerable in a climate change scenario. Water quality is not a problem, but may become so due to the low levels of wastewater drainage and treatment	Agriculture is relevant for the regional economy and most of the population is employed in water dependent sectors. Agriculture is profitable, particularly for the largest landowners. Farmers are concerned with the diversification of revenue stream. Water and energy costs are relevant, although water pricing is not implemented	Income of agricultural workers is low, when compared to regional average, and the distribution of opportunities and income is still rather unequal. Access to medical care and social security for agricultural workers could also be improved	Institutions in are committed to balance stakeholders' needs and have the capacity to ensure efficient water management
	The perimeter was developed aiming at an economic production to provide sustainability to farmers. Currently the irrigated area produces: rice, beans, banana, coconut, soursop and grass cutting. Other activities include cattle for milk production, meat production and livestock breeding				Stakeholder participation in water management is well established in the area, although mainly through representative processes

(*Continued*)

Table 3. (*Continued*)

Pilot area	Description	Environmental integrity	Economic resilience and profitability	Social well-being	Good governance
Forquilha (Brazil)	Forquilha is contained in the sub-basin of the river Banabuiú that comprises the central hinterland of Ceará state more strongly subject to drought The area is small and irrigated agriculture corresponds to a small share. 50 to 100 families are directly involved, using drip and sprinkler irrigation systems The main crops are maize, beans, horticultural crops and forage	This area is dependent from a water source (groundwater) that is highly vulnerable to climate change. There is potential to improve water productivity for some crops. Water quality problems (salinization) and poor soil quality are also reported	Agriculture is relevant for the regional (Quixeramobim) economy, but it is not profitable being mostly for self-supply. The capacity to develop a market-oriented agriculture is very limited. Water and energy costs are relevant, although water pricing is not implemented. A scheme for water pricing needs to be implemented to provide incentives for water efficiency and guarantee the quality of irrigation services	Poor working conditions and qualification of agricultural workers, as well as perceived unfairness in the distribution of opportunities and income are major concerns. The population is fairly stable and people have a fair sense of belonging to the community	One of the main problems is the lack of a formalized basin committee, which hinders the resolution of conflicts that arise particularly in dry years and limits the capacity to manage resources. The community has a very poor awareness regarding the rules for water management and water allocation is perceived as being unfair. The creation of a local watershed committee is seen as a priority to ensure good governance of water
Mayo River (Mexico)	Located in Norwest Mexico, in Sonora State. The Adolfo Ruiz Cortinez dam was built to use the surface runoff from the Mayo River. Within the area of the irrigation district there are 130 deep wells. All cultivated area is irrigated and the main crops are wheat, safflower, potato and vegetables Users of the irrigation districts and officials of the National Water Commission are aware that improving water use efficiency can achieve better productivity	This area is highly dependent on irrigation, facing water scarcity problems, with an unreliable source and high vulnerability to climate change. The water productivity for some crops is low. In a scenario of severe water scarcity irrigated agriculture is not resilient	Agriculture is the main economic activity. However, profitability varies across crops and the sector depends on a limited number of cultures. Highly dependent on public subsidies, which support wheat and safflower crops. Investment in agriculture is increasing slowly. Water and energy costs are not very relevant, since the irrigation system is gravitational. The existing volume-based water pricing scheme should be adjusted to promote efficiency	Working conditions are poor and opportunities and income are not fairly distributed. A percentage of population is not covered with social security. Qualification of agricultural workers is at the elementary level	There is adequate institutional capacity to promote water management and the rules are perceived as clear and fair. However, a more direct involvement of the population in decision-making processes would be desirable

(*Continued*)

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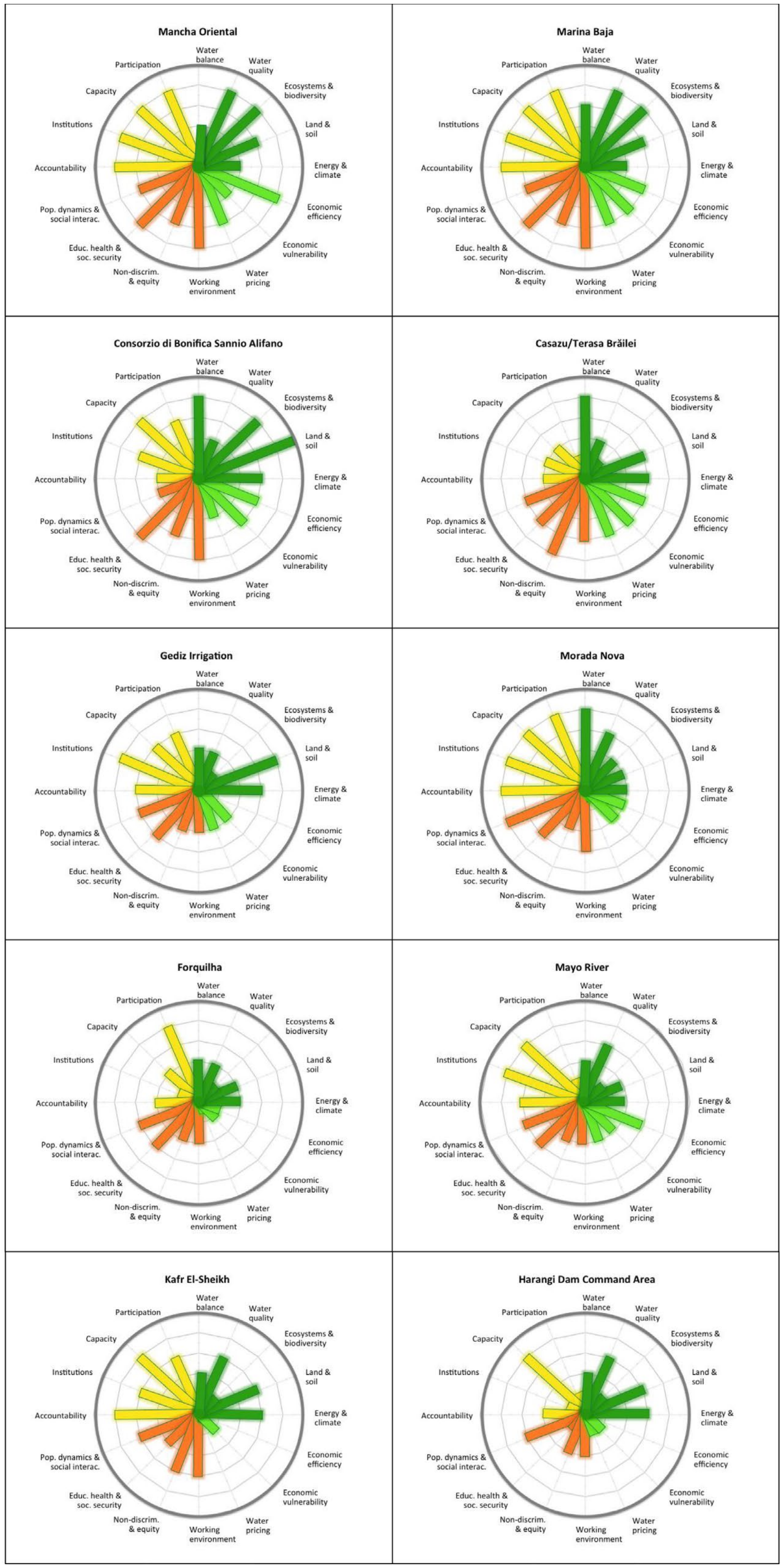
Table 3. (*Continued*)

Pilot area	Description	Environmental integrity	Economic resilience and profitability	Social well-being	Good governance
Kafr El-Sheikh (Egypt)	Kafr El-Sheikh Governorate lies in the middle north of the Nile Delta. The irrigation scheme covers an area of 3,382 ha, of which 2,938 ha are cultivated and irrigated. The main crops are: rice, maize, sugar beet and wheat. There is increasing rural poverty and food insecurity. There is a lack of coordination between organizations with respect to planning and implementation of physical intervention at the governorate level. Farmers lack the awareness for the safe re-use of water	Agriculture is highly dependent on irrigation, from surface water and water scarcity is a constraint. Agriculture is highly intensive in energy, since all water is pumped from the river, and the area is considered moderately vulnerable to climate change	Agriculture is a very important economic activity, moderately profitable. Agriculture is mainly market-oriented, although food self-supply is also relevant. Investment in agriculture is increasing, but it is highly dependent on public subsidies. The economic productivity of water is low for all the main crops, and in particular for sugar beet. A scheme for water pricing needs to be designed and implemented	The average salary in agriculture is 10% lower than the region average. The working conditions are perceived as fair and workers have a fair access to medical care, but only 30% of the population is covered with health and social security. There is a very low rate of adult literacy, but the agricultural workers are considered as qualified The population is expanding. There is a strong engagement of local population in civil society organizations, since farmers are involved with local water organizations	Local authorities seem strongly committed to consider stakeholder needs in decision-making processes. Water allocation rules are perceived as fair. However, there are conflicts regarding water allocation. These conflicts are solved through round tables within customary councils
Harangi Dam Command Area (India)	Located in Southern Indian State of Karnataka. Harangi is a tributary of River Cauvery. The majority of farmers in the region are subsistence farmers where 90% of farms are only 0.3 ha in size. The main crops are paddy and finger millet As Cauvery is an interstate river, conflict often arises with the neighboring state Tamil Nadu	Agriculture is highly dependent on irrigation and water scarcity is a constraint Tailenders and some pockets of command area are vulnerable to drought. Energy intensity is low and vulnerability to climate change is moderate	Agriculture is very relevant for the regional economy and it is mainly oriented for food self-supply. Water and energy costs are not relevant. The existing area based water pricing scheme should be adjusted to promote efficiency, while considering farmers' capacity to pay	Working conditions are perceived as fair, but refer to basic facilities. The population is not covered with health and social security. There is a low rate of adult literacy in the region	Institutions to promote water management are still generally lacking and participation is limited. The main challenges for the future are the obstacles to farmer participation in decision-making and the lack of accountability and transparency

adoption of sustainable management practices (eco-conditionality) may play an important role in leveraging transitions towards more sustainable agriculture.

It is important to ensure a fair distribution of opportunities and income in society—this means fairness in access to resources between small and large farmers, balance in salaries between agricultural workers and other economic sectors and fairness of opportunities across genders. Even in areas where social well-being is perceived as good (e.g. Spain and Italy) the still unequal distribution of opportunities and income between agricultural and non-agricultural workers leads to abandonment of agricultural activities, emigration and a shrinking population. In some areas (e.g. Brazil, Turkey, India) working conditions in agriculture are still unsatisfactory and access to education and

Figure 3. Sustainability profiles for the pilot areas.



medical care is still poor, pointing directly to a high priority of actions in these domains to improve sustainability performance of these agricultural systems.

Clear and accepted water allocation rules, coupled with strong institutions and technical capacity are fundamental governance elements. Without these it is impossible to promote sustainable water use, enforce decisions and handle water allocation conflicts in an equitable manner. In some of the studied areas, (e.g. Italy, Romania) accountability and capacity of water management authorities are issues of concern regarding governance. In all areas, there is a perception that a more direct involvement of farmers and a higher transparency in decision-making processes regarding water management could contribute to obtain better solutions, building a sense of ownership towards the decisions taken, fostering social learning and strengthening community relations.

Technologies and farm advisory services, such as the ones developed in the SIRIUS project, can be used as an entry point to promote improved water governance and increase water use efficiency in irrigated agriculture. They can play a very important role and contribute to the development of a shared understanding and a new mind-set regarding water management problems and solutions among the different stakeholders.

5. Conclusions

The proposed framework for sustainability assessment of irrigated agricultural systems brings a new perspective in this domain by adopting an encompassing understanding of sustainability, incorporating concepts of both resilience and persistence. It combines the evaluation of the conditions of the natural system that supports agricultural activities with an assessment of central elements required to ensure a flourishing livelihood for rural populations. The emphasis on the irrigation perimeter/watershed scale is also an important aspect of this framework, that enables the understanding of the links between the ecological system, agricultural competitiveness and the living conditions of the population.

The regional teams involved in the application of the framework in the pilot areas acknowledged that this exercise allowed them to gain a wider perspective and a deeper understanding of the main issues of concern. It also allowed them to grasp the main inter-linkages between the different sustainability dimensions. Even in those areas where data available were scarce, such as the case of the India pilot area, the framework proved to be useful and applicable, although it was not possible to obtain quantitative values for many indicators.

Another important feature of this framework is the process that led to its development, which combined a theory-based proposal with inputs from stakeholders engaged in agricultural research and practice from different parts of the world, representing very different contexts. This has contributed to enrich the framework, while making it simple and robust enough to be of general applicability.

The application of the SIRIUS framework proved the usefulness of this approach to obtain a holistic picture of sustainability in irrigated agriculture areas in different contexts. It allowed users to understand “where they are”, so that they could then define a strategy to move towards “where they want to go” (the sustainability vision). Therefore, the results of the application of the SIRIUS framework are particularly meaningful for the social actors in each area. Their discussion can be a starting point for the organization of participatory processes aimed at developing a shared vision for sustainability in an irrigated agricultural area and the roadmap to get there. In this process, stakeholders are encouraged to think about their area and their agricultural activity, identifying what are the main bottlenecks and opportunities for a transition towards a sustainable future.

The adoption of such a framework to measure agricultural sustainability can also be useful to serve as a guiding tool to support the design and implementation of long term monitoring programs of irrigated agricultural systems and associated practices and policies aiming at a more sustainable farming sector.

Supplementary material
The supplementary material for this paper is available online at https://doi.10.1080/23311932.2017.1323542.

Acknowledgements
The authors would like to thank the collaboration of the stakeholders in all pilot areas that have contributed with their knowledge, perceptions and viewpoints for this research. We are also grateful to the two anonymous reviewers who provided valuable comments and suggestions for improvement.

Funding
The research presented in this paper was carried out with the support of the EU-funded project Sustainable irrigation water management and river-basin governance (SIRIUS): implementing user-driven services, FP7-SPACE-2010-1 [grant agreement number 262902]. CENSE is financed through Strategic Project Pest-OE/AMB/UI4085/2013 from the Fundação para a Ciência e Tecnologia, Portugal.

Competing Interests
The authors declare no competing interest.

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Citation information
Cite this article as: A holistic framework to assess the sustainability of irrigated agricultural systems, Paula Antunes, Rui Santos, Inês Cosme, Anna Osann, Alfonso Calera, Dirk De Ketelaere, Anna Spiteri, Miguel Fernández Mejuto, Joaquín Andreu, Andrea Momblanch, Pasquale Nino, Silvia Vanino, Violeta Florian, Mihai Chitea, Cem Polat Çetinkaya, Meiry Sayuri Sakamoto, Milton Kampel, Luis Alberto Palacio Sanchez, Alaa El-din Abdin, Ravikumar Alanasiddaiah & Sashikumar Nagarajan, *Cogent Food & Agriculture* (2017), 3: 1323542.

Notes

1. For example, organic farming focuses mainly in the environmental dimension (although recently its scope has been enlarged to account also for social aspects), while sustainable intensification relates the environmental and economic dimensions, by focusing on the goal of enhancing agricultural production while reducing environmental impacts.
2. http://www.iap2.org/

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