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Research paper

How water amounts and management options drive Irrigation Water Productivity of rice. A multivariate analysis based on field experiment data

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ABSTRACT

Rice cultivation is globally hampered by several conditions, which urge farmers to maintain adequate production levels while properly managing irrigation water. This has noticeable repercussions on the efficient use of the resource and on water productivity. Nonetheless, more often, this latter topic is addressed by estimating the respective values, without deeply investigating the possible causes behind such discrepancies. The main objective of this paper is to overcome such limitations, by (i) providing a comprehensive and updated overview of Irrigation Water Productivity (IWP) for rice, and (ii) exploring the role of irrigation water in determining IWP value. The analysis of experimental data collected from 51 studies reveals IWP to vary between 0.09 and 8.10 kg m^{-3}, with mean and median values of 1.36 and 0.85 kg m^{-3} respectively; moreover, a non-linear relationship between irrigation water amounts and IWP (r^2 = 0.81) is depicted. Further on, data are analyzed using an econometric approach. Specifically, a multivariate linear regression model is used to shed light on the joint contribution of water inputs, regime and irrigation method to productivity. This demonstrates the significant roles of irrigation ($\beta = -1.006$) and rainfall ($\beta = 0.062$) amounts, while aerobic regime and irrigation method is proved to be a further key driver ($\beta = -0.305$). Such results enable identifying the elements to be enforced, if increasing IWP for rice is the prime objective. Finally, some implications are derived for water policy and the connections with weather-climatic and environmental conditions that are globally affecting the availability of water in agriculture.

1. Introduction

With more than 162 Million hectares cultivated worldwide (FAOSTAT, 2014), rice is one of the leading food crops, and rice-farming a strategic activity for several countries. Rice-based farming systems are particularly relevant for the rural poor in Asia, Latin America and Africa, where agriculture has a prominent subsistence role. There, it contributes in ensuring food sustenance (Mancosu et al., 2015), fostering local development and economic livelihood for farmers (FAO, 2004), preventing social unrest driven by volatility of commodity prices (IRRI, 2013). In many parts of the world, rice-farming is characterized by a marked specialization, which makes the relevant sector highly competitive and profitable. In this case, most of the final product is oriented to global markets and commercialized via international trade. In these areas, the economic importance of the sector can be substantial, so as its contribution to the economic viability. Furthermore, rice cultivation provides many ecosystem services (Matsuno et al., 2006), used as evidences of the advisability to preserve the activity. Amongst others, the environmental value of submerged paddy fields (Yoon, 2009), the creation of wetland habitats and protected areas (Natuhara, 2013), the aesthetic quality of traditional landscapes (Jung and Ryu, 2015).

At the same time, manifold conditions globally hamper the rice sector, affecting both production and competitiveness of rice-farming. For instance, the volatility of paddy rice prices (FAO, 2016) may not compensate for production costs (Ferrero and Nguyen, 2004), while in some Countries, where rice is a heavily protected good, it often faces smuggling problems (Golub, 2012). However, major concerns are mostly related to water resource, both in terms of quantity and quality. In the first instance, they arise as a problem of water availability. Shortcomings due to climate-induced effects (Olesen et al., 2011) have determined the occurrence of hot-spots of water scarcity in several areas (Bouman et al., 2007), further exacerbated by recurring and intensive droughts events. This preponderantly influences the possibility of an adequate resource

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allocation amongst sectors (Elliot et al., 2014), users and even crops within the same production pattern (Bischetti et al., 2014). In addition, even if not quantitatively limited, irrigation water may suffer from a deteriorated quality. Soil salinization and resource pollution in general may lead to a lower usability and a scarcer rice production (Clermont-Dauphin et al., 2010; Isquierdo Fraga et al., 2010). This array of conditions urges rice-farming to maintain adequate production levels, while properly managing production factors. Consequently, an optimal and rational use of the resource becomes a prime objective, possibly encouraged and sustained by water policies operating at regional or supra-national level (e.g. European Water Framework Directive). From this point of view, the adoption of water saving techniques is increasingly stimulated to mitigate the effects of climate change or to release water that would allow expanding cultivated areas.

Crop yield tends to be proportionally affected by the amount of irrigation water received (Maeda et al., 2011) and farmers' decisions should properly balance between yield and resource use (Monaco et al., 2016). In this perspective, several authors rely on the concept of "water productivity" (Molden, 1997) to assess the success of different cultivation practices (e.g., Brauman et al., 2013; Lenton, 2013; Molden et al., 2010). Though, the productivity-based approach simplifies real conditions and doesn't embark a large set of stochastic events, risks and random shocks beyond farmers' control. Additionally, it fails in providing adequate information about the use of resources. For these reasons, water productivity as a sole indicator conveys too limited information and does not allow to deduce helpful insights on the efficient, rational, optimal use of irrigation water (Seckler et al., 2003). Quoting from Wichelns (2015), likewise, estimations of productivity and yields over time and locations inadequately indicate desirable changes, either in water management practices or in production results. The author also recognizes that most of the studies only estimate water productivity, without discussing the plausible causes behind the observed discrepancies amongst values. According to a FAO survey (FAO, 2003), water productivity in agriculture strongly augmented in the period 1961–2001, mostly thanks to yield increase. In rice-farming, this is even exacerbated in recent times, by the time the sector has been experiencing the introduction of short-cycle, high yielding cultivars and ameliorated varieties (e.g., Clément and Louvel, 2013) suitable for the cultivation under limited water supplies. The "more crop per drop" paradigm (Kijne et al., 2003) may benefit from such innovations (Ben Hassen et al., 2016), which contribute to stabilize or increase grain yield. On the other hand, Zwart and Bastiaanssen (2004) ascribe variability of water productivity also to climate conditions; indeed Irrigation Water Productivity for rice was estimated during both the rainy season (e.g., Sarkar et al., 2002; Pandey et al., 1989; Islam et al., 1986), and summer (e.g., Uppal et al., 1991; Hassan et al., 1989; Marimuthu and Lulandaivelu, 1987; Islam et al., 1986). It must also be recognized that irrigation water management is a further source of variability, but scarce evidences about this are provided.

Starting from these considerations, the study at hand aims at deepening how water inputs and irrigation strategies drive productivity of rice. To our best knowledge, a comprehensive and updated overview of its productivity values is still missing. The only study addressing to this topic was carried out by Zwart and Bastiaanssen (2004), who reviewed crop water productivity for rice and other irrigated crops. This analysis could rely upon a small number of publications and trials and was limited to highlight the variation of productivity with respect to individual independent variables. The main objective of our analysis is to overcome such limitations, exploring the role of irrigation water in determining productivity. An extensive literature review was carried out to collect a large set of published experimental data. Afterwards, the analysis was conceived on an econometric basis; specifically, a multivariate linear regression model was used to shed light on the joint contribution of water inputs (i.e., supplied amounts), regime and irrigation method to productivity. The next section introduces both conceptual and methodological approach, then results are presented and discussed. Finally, some insights to address irrigation water policies are derived.

2. Conceptual and methodological approach

2.1. Irrigation water productivity

Traditionally, rice cultivation requires the use of a large amount of water. Irrigation water might account for most of the resource used at farm-level, despite in some cases it might be small (Barker et al., 2003). This is even more valid for arid and semi-arid regions, where agriculture is mostly or fully dependent on irrigation. Besides, farmers can directly intervene on irrigation volume. Whereas facilitate and affordable access to water is at farmers' disposal, they generally have large influence and control over water volumes, timing and supply (Wichelns, 2015). Irrigation water is thus a key element for rice-cultivation practices; for this reason, water productivity is hereinafter referred to as Irrigation Water Productivity (IWP, kg m^{-3})

$$IWP = 100 * \frac{P}{I} \tag{1}$$

where P is the paddy rice yield (t ha^{-1}) and I the seasonal irrigation water volume (mm).

2.2. Data sourcing and collection criteria

A review of international literature of the last twenty years was carried out to select a substantial number of studies concerning (i) the use of water inputs on rice as the sole crop, and (ii) their respective production performances. It was aimed at collecting data and information from field experiments performed worldwide. During this time-span – though the development of new practices and the improvement in the use of production factors – no marked modifications in the rice-production system occurred. Consequently, the influence of new techniques on the rice sector can be considered minimal, and the conditions of the production sector quite stable.

A large dataset was created based on experimental data from studies that provided some precise information. Only measured values were considered, while results from water balance simulations and yield-predictive models were excluded. Papers should (i) indicate the precipitation amount occurred at the experimental site during the growing season, (ii) report minimally two data between Irrigation Water Productivity, yield and irrigation amounts and (iii) clearly indicate how irrigation water was administered. Each value was considered individually, while average values – per experimental year or management strategy applied – were not included in the data set.

A great variability in locations (climate and soil type implications), agronomic choices (e.g., fertilization rates, rice cultivars) and water use was noticed. Such a complexity reflects the heterogeneity of agricultural practices and the possible combinations of production factors that may be adopted at farm-level (Zwart and Bastiaanssen, 2004). Similarly, a large array of irrigation strategies was found. To facilitate the subsequent analyses and explore their contribution to the variability of IWP, such strategies were firstly grouped under the water regime performed, i.e., flooding irrigation or aerobic rice, and then further differentiated on the basis of irrigation method and water management (Table 1).