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Impact of different water and nitrogen inputs on the eco-efficiency of durum wheat cultivation in Mediterranean environments

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ABSTRACT

The present study addresses the eco-efficiency (environmental and economic trade-offs) of durum wheat cultivation practices adopted at field level under typical Mediterranean conditions of Southern Italy. This study is based on three years of experimental data of durum wheat cultivation under three water supply regimes (full irrigation, 50% of full irrigation and rainfed) coupled with two nitrogen (N) fertilizer levels (high N, HN: 120 kg/ha, and low N, LN: not fertilized). The environmental impact assessment was based on a novel life cycle impact assessment method which quantifies seventeen midpoints (problems-oriented) and three endpoints (damage-oriented) indicators using ReCiPe 2016 model. The economic performance was evaluated using the total value added to the system's final products due to water and N use and applied management practices. Eco-efficiency was assessed as a ratio of the total value added to the environmental impact categories. The water consumption impacts were estimated in addition to the typical environmental impact categories. The high input (irrigation and fertilization) intensity systems resulted in higher agricultural production, however, produced greater impacts on water consumption, global warming, and energy-related indicators. In turn, these impact categories generated the damages to human health, ecosystem quality, and resource scarcity. The analysis demonstrated that eco-efficiency cannot be always compensated by higher yield and corresponding economic total value added. The eco-efficiency assessment indicated that agronomic practices with the low use of resources (e.g., deficit irrigation with low N) tend to have higher eco-efficiency than more intensive cultivation strategies. Hence, the sustainable crop production strategies should evolve towards the adoption of precision agriculture and optimization of water and fertilization inputs (in space, timing, and quantities) that can improve yield response to resources, environmental and economic performance. In this sense, life cycle thinking and assessment considering multiple impact categories are essential to support decision-making processes towards sustainability.

1. Introduction

The global demand for wheat is expected to increase by 60% by 2050 (Dixon et al., 2009). The bulk of the projected growth in crop production will be due to the intensification of cultivation, i.e. increased fertilizer and water use, and energy consumption. At the same time, the environmental pressures posed through intensified agricultural activities will likely increase. Hence, the selection of the site-specific and resource-optimized management practices and crop varieties is to increase/stabilize yields and water productivity (Todorovic, 2016).

In the Mediterranean region, the assessment of eco-efficiency of food supply chain, resource management policies, and on-farm agronomic measures is of great importance to preserve limited natural resources and assure sustainable ecosystems functioning and resilient rural development. Therefore, the intensification of crop production has to be supported by the optimization of resource use efficiency and agronomic measures able to improve the environmental performance of the agricultural systems. In this context, the life cycle thinking is increasingly seen as a key concept for systematically analyzing farming practices, thus ensuring the transition towards more sustainable production and consumption patterns (Notarnicola et al., 2017; Sala et al., 2017).

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Life Cycle Assessment (LCA) methodology is frequently used for calculation of potential environmental impacts of material and energy inputs of product or processes (ISO, 2006). Many studies, with a wide geographic context, have been conducted using the LCA approach to analyze the environmental impacts of wheat production systems. Charles et al. (2006) used a multi-impact LCA analysis of wheat crop with different intensities of production in Switzerland. Biswas et al. (2008) presented a greenhouse gas (GHG) life cycle assessment of wheat production in an Australian context. Meisterling et al. (2009) used a streamlined hybrid LCA to compare the global warming potential (GWP) and primary energy use of conventional and organic wheat production in the US. Tahmasebi et al. (2017) investigated the productivity and environmental impacts of irrigated and rainfed wheat production systems in Iran highlighting the need for better balancing between productivity and sustainability. Recently, Ali et al. (2017) have elaborated the effect of different levels of soil disturbance and nitrogen inputs on the greenhouse gas emissions of durum wheat cultivation in Southern Italy. However, these studies focused on some specific indicators of environmental aspects of wheat cultivation and did not consider the impact of different water inputs and the economic aspects of eco-efficiency. Henceforth, the development of metrics for measuring environmental impacts of a product or service system along with its economic performance is needed to explore the trade-off between economic and environmental sustainability (Georgopoulou et al., 2016).

In the recent years, the concept of eco-efficiency has been promoted to embrace ecological and economic aspects of production towards the site-specific and resource optimized management practices (Keating et al., 2010; Park et al., 2010; Todorovic et al., 2016). The eco-efficiency can be applied as a composite indicator for the evaluation of agricultural systems on the road toward sustainable intensification of production (Gadanakis, 2014).

The Mediterranean environments are characterized by chronic water shortage and irregular precipitation pattern. Thus, the adoption of supplementary irrigation and its interaction with nitrogen input are of primary importance to stabilize cereal production in the region (Oweis et al., 1998; Abi Saab et al., 2015). The present study applied a systemic analysis to assess the eco-efficiency of durum wheat cultivation under various management strategies adopted at field-level in Southern Italy. The study explored the effects of different irrigation and nitrogen inputs, and corresponding agricultural practices with special focus on environmental sustainability, and it quantified the eco-efficiency performance of the implemented management options.

ReCiPe 2016 (Huijbregts et al., 2017) the most recent harmonized life cycle impact model including seventeen midpoint and three endpoint impact categories was employed to highlight the importance of all of the potential environmental impacts. The broadest set of impact categories includes also water consumption, one of the emerging categories with the greatest interest to the LCA of agricultural production systems in the Mediterranean region. The environmental impact of water consumption is determined both at the midpoint (water consumption) and at endpoint level (damage to the ecosystems and human health). The adoption of such approach supports stakeholders and policymakers in analyzing the agricultural systems and identifying the best mitigation/adaptation options of mutual interests and for more eco-efficient agricultural production (Levidow et al., 2014; Mehmeti et al., 2016).

2. Materials and methods

The methodology was based on a combination of the LCA (ISO, 2006) and the assessment of the Total Value Added (TVA) to the system's final products due to water and nitrogen use and applied management practices.

2.1. Goal definition, functional unit, and system boundaries

In this study, the agricultural production system corresponded to the agronomic practices adopted for durum wheat cultivation in Puglia region (Southern Italy). The production system under study considered both foreground and background systems (Fig. 1), and included a set of life cycle production stages (S), namely, land preparation, i.e. soil tillage and land leveling (S1), sowing (S2), growing (S3) and harvesting (S4).

The operational data (i.e. use of resources, agronomic practices, and corresponding yield response) for default operations were collected from three years of field research experiments carried out in 2005–2006, 2006–2007 and 2007–2008 at the Mediterranean Agronomic Institute of Bari (Italy). The study site and experimental setup were described in details by Albrizio et al. (2010). The scope of the present study was defined as "the cradle to the gate of the field" and included the adopted agronomic practices, i.e. different water and nitrogen inputs and corresponding energy consumption during the farming season as well as the use of pesticides and materials for equipment (tractor and irrigation system) production. Two functional units (FU) were defined as: (a) 1 ha of cultivated land, i.e. based on the land occupation, and (b) 1 t of wheat obtained under different management strategies and delivered to the farm gate, i.e. based on the product unit. All the resources, emissions and LCA (i.e. values of the selected environmental indicators) were linked to both FUs. The intended audience analysis included farmers, agricultural advisors/policy makers, water users' associations, farmers' cooperatives and environmentalists. Since co-products are not harvested in this study, no allocation criteria were used.

2.2. Life cycle inventory (LCI) flows modeling

In this study, wheat cultivation implied crop inputs (i.e. seeds, fertilizers, water, fossil fuels, and pesticides) and corresponding grain yield achieved (Table 1). These data were used in the life cycle impact assessment (LCIA) stage to understand and evaluate the magnitude and significance of the potential environmental impacts of the adopted management practices. Wheat eco-efficiency performance was assessed under six management strategies (Table 1), i.e. three water supply regimes (100%W, 50%W, R corresponding to full irrigation, 50% of full irrigation and rainfed) coupled with two N fertilizer levels (high N, HN: 120 kg/ha and low N, LN: not fertilized and relying only on N available in the soil at sowing time).

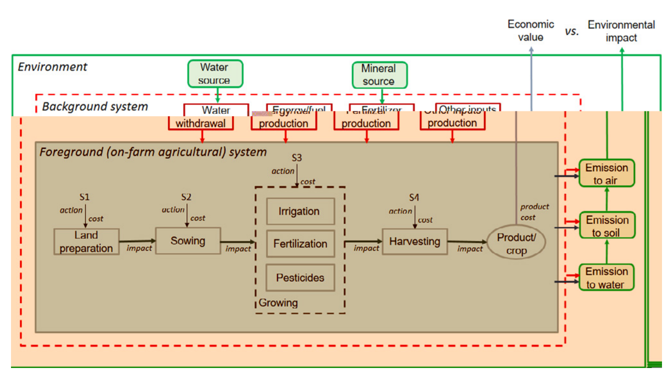

Fig. 1. System boundaries and life cycle stages (S) adopted for the eco-efficiency assessment of on-farm wheat cultivation.