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Assessing changes in eco-productivity of wastewater treatment plants: The role of costs, pollutant removal efficiency, and greenhouse gas emissions

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ABSTRACT

Improving eco-efficiency of wastewater treatment plants (WWTPs) has been identified as being essential for achieving urban sustainability. Several previous papers have evaluated the eco-efficiency of WWTPs using data envelopment analysis (DEA) models. However, those models provided only a static assessment in that they ignored possible fluctuations over time within each plant. To overcome this temporal limitation, this paper evaluates dynamic eco-efficiency (changes in eco-productivity over time) of WWTPs using the dynamic weighted Russell directional distance model (WRDDM). This approach allows one to obtain an eco-productivity change index for each major component of the WRDDM model (costs, pollutants removal, and greenhouse gas emissions). Our results illustrate that although eco-productivity improved in half of the WWTPs we assessed, there was still potential for improving some eco-efficiency components. Moreover, operational costs and greenhouse gases emissions were the main drivers reducing eco-productivity. This paper demonstrates the importance of evaluating change in eco-productivity over time and in identifying the drivers associated with those changes, both of which can be used to support decision-making focused on the sustainability of WWTPs.

1. Introduction

In 2016, Sustainable Development Goals of the 2030 Agenda for Sustainable Development adopted by world leaders took effect (United Nations, 2017). Improving eco-efficiency is considered to be an essential approach for easily reaching sustainable development goals (Chen et al., 2017). In this context, the United Nations Industry and Development Organization (UNIDO) identified eco-efficiency as one of the major strategic elements in its work on sustainability (UNIDO, 2012). The concept of eco-efficiency was first defined by Schaltegger and Sturm (1989) as the ratio between amount of environmental impact and value added. In other words, eco-efficiency entails producing more goods and services with fewer resources, and with less environmental impacts (Beltrán-Esteve et al., 2017).

Wastewater treatment is essential for protecting human health and environmental sustainability (IOC/UNESCO, 2011). A wastewater treatment plant (WWTP) is a special type of productive unit that both uses energy and materials to remove pollutants from wastewater and discharges pollutants (suspended solids, organic matter, nutrients) into the environment (Ren and Liang, 2017). The ability to quantify eco-efficiency of WWTPs is essential for determining success, identify and track trends, prioritize actions, and identify areas for improvement. Hence, in recent years, a series of research studies have been aimed at assessing the eco-efficiency of WWTPs (Molinos-Senante et al., 2016a). However, given the multidimensionality of the eco-efficiency concept, developing assessment protocols is a complex task.

Life-cycle assessment (LCA), data envelopment analysis (DEA) and a combination of them (LCA + DEA) have been conventionally employed to evaluate the eco-efficiency of WWTPs (Larrey-Lassalle et al., 2017; Laitinen et al., 2017; Lorenzo-Toja et al., 2017; Guerrini et al., 2017). LCA is a robust method used to quantify the global environmental impact of a functional unit (Bidstrup, 2015) and therefore, LCA quantifies environmental impacts of WWTPs in much more detail than DEA. However, LCA does not consider economic variables in its assessment,

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which is an important shortcoming. It should be noted that in the term eco-efficiency, the prefix "eco" represents both ecological and economic performance (Yin et al., 2014). In contrast, DEA provides a synthetic performance index that integrates multiple inputs and multiple outputs (economic and environmental) (Cooper et al., 2007). DEA method presents an additional and fundamental advantage: it enables to integrate environmental impacts in the eco-efficiency assessment as undesirable outputs. By contrast, in LCA and LCA + DEA they are integrated in the assessment as inputs. However, several papers have evidenced the limitations of this approach (Pérez et al., 2017) since treating undesirable outputs as inputs does not reflect the real production process. Hence, DEA is superior to LCA in evaluating and comparing the eco-efficiency of WWTPs (Dong et al., 2017).

Given the advantageous features of the DEA approach, several DEA models have been used to evaluate the eco-efficiency of WWTPs, by considering economic variables as inputs and pollutant-removal efficiency as outputs (e.g. Hernández-Sancho et al., 2011; Sala-Garrido et al., 2012; Guerrini et al., 2015; Tomei et al., 2016; Dong et al., 2017). Within the framework of DEA, eco-efficiency can be evaluated by incorporating environmental impacts as undesirable outputs generated by the productive process (Luptacik, 2000). Eco-efficiency evaluations of WWTPs integrate three components into a synthetic index, namely: i) desirable outputs (pollutants removal efficiency), which should maximized; ii) inputs (economic costs) to be minimized; and, iii) undesirable outputs (environmental impacts), which should minimized (Liu et al., 2017). The great advantage of using this approach is that the index holistically integrates the three dimensions of eco-efficiency, specifically service value, resource consumption, and environmental impacts (Ji, 2013).

The integration of environmental impacts, as undesirable outputs, has been widely considered in eco-efficiency assessments for several types of production systems, such as cement firms (Oggioni et al., 2017), agricultural units (Pan and Ying, 2013), coal-fired power plants (Liu et al., 2017), tourism destinations (Peng et al., 2017), among others. However, in the framework of WWTPs, only Molinos-Senante et al. (2016a) integrated an environmental impact (greenhouse gas (GHG) emissions) as an undesirable output when evaluating eco-efficiency. In this integration, they employed the weighted Russell directional distance model (WRDDM). This non-radial DEA model differs from radial DEA models in that it allows one to obtain an eco-efficiency index for each input and output (both desirable and undesirable) involved in the analysis, in addition to generating a global efficiency index (Wei et al., 2013). In spite of the great use of previous studies evaluating the eco-efficiency of WWTPs (both integrating and not environmental impacts as undesirable outputs), they provided a static assessment. In other words, they assessed the performance of WWTPs for a given moment of time, without regard to potential changes over time within the WWTPs. Thus, this approach is purely static and cannot account for changes in the performance of WWTPs. However, in order to better support the decision-making process, information about temporal dynamics of eco-efficiencies is essential. Being able to assess changes in eco-productivity over time not only allows one to compute the eco-efficiency of a WWTP for any given time period, but it allows one to compare the eco-efficiency among WWTPs (Al-Refaie et al., 2016). By quantifying eco-productivity change over time, one can determine whether the eco-efficiency of units (WWTPs in this study) has improved or worsened over a given period of time (Mahlberg et al., 2011). The assessment of eco-productivity change involves extending the notion of eco-efficiency to an interporal setting (Mahlberg et al., 2011).

Despite the usefulness of evaluating the dynamic eco-efficiency of WWTPs, no studies have been published dealing with this issue. To overcome this gap in the literature, the main objective of this paper was to evaluate changes through time in the eco-productivity of WWTPs using the dynamic WRDDM. This model allowed us to quantify contributions of inputs and outputs (both desirable and undesirable) to changes in eco-productivity and its drivers (i.e., relative to changes in efficiency and changes in technology). This paper pioneers the use of the WRDDM approach by extending static eco-efficiency analysis to an inter-temporal approach. Moreover, our approach is the first attempt at evaluating the eco-productivity (eco-efficiency over time) of WWTPs by incorporating GHG emissions as undesirable outputs.

From a policy and management perspective, evaluating dynamic eco-efficiency (i.e., change in eco-productivity) of WWTPs is essential for developing long-term policies aimed at promoting sustainable wastewater treatment. Computing the effects of inputs and outputs on overall change in eco-productivity (and its drivers) provides valuable information for policy makers. For example, it allows policy-makers to identify whether changes in eco-productivity of WWTPs are driven by changes in economic costs, efficiencies in removing pollutants, and/or GHG emissions. This information is of value because it can be used to support policies and managerial strategies that improve the eco-efficiency of WWTPs. Quantifying changes in the eco-productivity over time is also very useful for evaluating the successes/failures of WWTP management practices and wastewater treatment policies adopted by water regulators.

2. Eco-productivity change and DEA methodology

Changes in eco-productivity of WWTPs were estimated by applying an approach proposed by Fujii et al. (2014). This approach is an extension of the WRDDM approach introduced by Chen et al. (2010) and Barros et al. (2012), which integrates a temporal dimension to conventional eco-efficiency assessments. It quantifies both the change in total factor eco-productivity (TFEPC) and the relative contributions of inputs and outputs (both desirable and undesirable) to the change (Fujii et al., 2017).

The dynamic WRDDM is based on a directional distance function combined with a non-parametric DEA approach (Molinos-Senante et al., 2016b). Considering that units (WWTPs in this study) use a vector of inputs ($x \in \Re_{+}^{N}$) to produce a vector of desirable ($y \in \Re_{+}^{M}$) and undesirable ($b \in \Re_{+}^{J}$) outputs, the directional distance function, as defined by Yang and Zhang (2016) is:

$$D(x,y,b;g) = \sup\{\rho\colon (x - \rho g_x, y + \rho g_y, b - \rho g_b) \in T\} \tag{1}$$

where $g = (g_x, g_y, g_b)$ is the vector that determines the direction in which inputs, desirable outputs, and undesirable outputs are scaled; ρ is the distance between the unit, (a WWTP in this study) and the efficient frontier.

$D(x,y,b;g)$ represents production inefficiency and so $D(x,y,b;g) = 0$ means that the unit is on the frontier, and therefore, is efficient. By contrast, if $D(x,y,b;g) > 0$, the unit is inefficient and has room to improve its performance (Zhou et al., 2014). Unlike the Shephard distance function, the directional distance function gives both the expansion (in desirable outputs) and contraction (in inputs and undesirable outputs) (Zelenyuk, 2014).

The Malmquist productivity index (MPI) and the Luenberger productivity indicator (LPI) are two widely-used models employed to evaluate changes in efficiency over time following a non-parametric approach. Nevertheless, Boussemart et al. (2003) determined that the LPI encompasses the MPI. Given that the LPI is a generalization of the MPI, in this study changes in eco-productivity of the WWTP were assessed by employing the LPI.

Based on the WRDDM, the TFEPC or the eco-productivity change between time t and $t+1$ for the k unit (a WWTP in this study) is described as follows (Fujii et al., 2014):

$$\begin{aligned} TFEPC_t^{t+1} = \frac{1}{2}\{ & D^{t+1}(x_k^t, y_k^t, b_k^t) - D^{t+1}(x_k^{t+1}, y_k^{t+1}, b_k^{t+1}) + D^t(x_k^t, y_k^t, b_k^t) \\ & - D^t(x_k^{t+1}, y_k^{t+1}, b_k^{t+1})\} \end{aligned} \tag{2}$$

where x_k^{t} is the input for year t, x_k^{t+1} is the input for year $t+1$, y_k^{t} is