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External costs of cadmium emissions to soil: a drawback of phosphorus fertilizers

Massimo Pizzol [a], James C.R. Smart [b], Marianne Thomsen [c,*]

[a] Department of Development and Planning, Aalborg University, Skibbrogade 5, DK-9000 Aalborg, Denmark
[b] Griffith School of Environment, Nathan Campus, Griffith University, 170 Kessels Road, Nathan, Queensland 4111, Australia
[c] Department of Environmental Science, Aarhus University, Frederiksborgvej 399, Postboks 358, DK-4000 Roskilde, Denmark

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A B S T R A C T

In this study the Impact-Pathway Approach methodology was applied for monetary valuation of health impacts due to cadmium emitted to soil as a micro-pollutant present in phosphorus fertilizers. Due to the high persistency of cadmium in soil, and high soil-to-plant transfer rates, humans are exposed to cadmium through their diet causing potential adverse health impacts. Future scenarios for cadmium emissions to soil via agricultural applications of inorganic and organic fertilizers in Denmark were defined. A simplified fate and speciation model allowed the increase in soil cadmium concentration to be calculated for each scenario. Human exposure was determined based on soil-crop bioconcentration factors for cadmium and dietary intake rates of Danish food crops. Updated dose–response functions linking lifetime cadmium intake to the probability of developing cadmium-induced renal disease and osteoporosis were applied. These impacts were converted into monetary values by using the EU standard value of a life-year adjusted for quality of life experience. Annualized cost per unit of phosphorus and cadmium are presented, discounted and undiscounted, for comparison. Application of struvite (magnesium ammonium phosphate) and mineral fertilizer produced the lowest external health costs, followed by the fertilizer products wastewater sludge and pig manure. The external cost estimates produced in this study could be used to design economic policy instruments to encourage use of cleaner fertilizer products.

1. Introduction

This study explores the impacts generated by the emission of cadmium (Cd) into soil, driven by agricultural demand for phosphorus-rich fertilizers. Cadmium is a metal with toxic proprieties; chronic, low-level exposure to cadmium has negative effects on human health, contributing to conditions such as diabetes, hypertension, and cancer (Amzal et al., 2009; Satarug et al., 2010). After smoking, diet is the main source of cadmium exposure; several studies associate chronic dietary exposure to cadmium with increased incidence of renal dysfunction and osteoporosis (EFSA, 2009; Satarug et al., 2010; Thomas et al., 2009). Dietary exposure to cadmium occurs when cadmium emitted to agricultural soil is taken up by crops that are consumed as food. This process is facilitated by the high persistency of cadmium in soil and by high soil-to-plant transfer rates (Smolders and Mertens, 2013).

Cadmium is emitted to agricultural soil by the application of inorganic and organic fertilizers. The cadmium content in mineral phosphorus fertilizers usually arises from the cadmium content of the phosphorous-ore from which these are produced (Cordell et al., 2011). Cadmium is also present as a micro-pollutant in the sludge and struvite (magnesium ammonium phosphate) produced from wastewater treatment plants. Organic fertilizers such as pig and cattle manure can also contain cadmium (Schwærter and Grant, 2003). Quantifying and minimizing emissions of cadmium to soil via fertilizer products are thus key steps towards a phosphorus life cycle which is supportive of sustainable agriculture (Cordell et al., 2011). Although recent research studies have focused on improving the energy efficiency of the phosphorus recovery process, the issue of cadmium contamination has not been systematically addressed (Johansson et al., 2008; Linderholm et al., 2012; Nakakubo et al., 2012).

Cadmium emissions could be reduced through economic or policy mechanisms by e.g. introducing taxes based on the cadmium

* Corresponding author. Permanent address: Department of Environmental Science, Aarhus University, Frederiksborgvej 399, Postboks 358, DK-4000 Roskilde (DK), Denmark. Tel.: +45 8715 8602.
E-mail addresses: massimo@plan.aau.dk (M. Pizzol), j.smart@griffith.edu.au (J.C.R. Smart), mth@dmu.dk (M. Thomsen).

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content of fertilizers. However, the societal costs of cadmium-related, phosphorus-driven impacts are not currently taken into account when the price of different phosphorus-fertilizers is set. Therefore, these cadmium-related impacts can be regarded as unquantified negative externalities; an "externality" being any impact which the actions of one economic agent impose on another, when those impacts are not accounted for within the economic system (Andersen, 2006). Adverse impacts which economic activities impose on the environment, and which carry no penalty price, can thus be considered to be negative externalities. Negative externalities can be "internalized" in the economic system by imposing on the externality producer a fee or charge which matches the cost which the externalities impose on adversely affected agents. Alternatively, production of cleaner fertiliser could be subsidized by the monetary value of the avoided externalities.

For either of these approaches, the cadmium-related external costs have to be determined via monetary valuation. The Impact-Pathway Approach (IPA) (European Commission, 2004) is a methodology for the monetary valuation of impacts associated with the emission of contaminants from human activities. The IPA is a bottom-up approach and consists of four steps: (i) definition of emission scenarios, (ii) modelling of the contaminant's fate in the environment and of human exposure to that contaminant, (iii) use of dose–response functions to determine exposure-related health impacts, and (iv) monetary valuation of these impacts. External costs have been calculated via IPA for atmospheric emissions of CO_2, NO_x, PM etc. (European Commission, 2004). IPA has also been applied to assess diffuse agricultural pollution due to nitrates (Andersen et al., 2011; van Grinsven et al., 2010) and pesticides (Fantke et al., 2012). A few examples also exist of IPA applied to study emissions of persistent trace pollutants such as metals (Bachmann, 2006; European Commission, 2007; Pizzol et al., 2010; Spadaro and Rabl, 2004). Calculating the external costs of metal emissions is challenging, however, since metal-specific fate models are required to decrease the modelling uncertainty and to account for metals' persistence in the environment over appropriately lengthy timescales (Bachmann, 2006). Moreover, the impacts and costs to future generations must also be accounted for, making the choice of time horizon and discount rate key modelling parameters.

In this context, this study was designed to determine the negative externalities generated by inorganic and organic phosphorus fertilizers, quantified as the external costs of health impacts attributable to cadmium emitted to soil following fertiliser applications over a specified time horizon. A secondary objective was to determine the robustness of the methodology by investigating the influence of different modelling parameters on the final results.

2. Materials and methods

Monetary valuation was performed via IPA taking Denmark as the case study area. The four modelling steps are described in the following subsections: units are reported in square brackets; values of each input parameter are reported in Table 1 and Table 2.

2.1. Fertilizer product emission scenarios

The emission scenarios assumed that a fertilizer is applied to agricultural soil for 95 consecutive years (starting from year 2010), resulting in a constant yearly emission of cadmium to soil, according to the cadmium content of each of the fertilizers (Table 1). The time horizon was chosen to study the impacts of chronic, long-term exposure to cadmium, as impacts will occur in the future depending on the extent of cadmium accumulation in soil and as its consequences following ingestion into the human body. Multiple generations will therefore be affected and a maximum cohort-age of 95 years was thus adopted for the model setup, matching demographic data available from Danish statistics (Statistics Denmark, 2012). Nine emission scenarios were defined: each differed regarding the fertilizer product applied and its phosphorus and cadmium content. The first six emission scenarios featured wastewater sludge as organic fertilizer. Sludge quality varies across Wastewater Treatment Plants (WWTPs) depending on the number and nature of industries within their catchment area, the plant capacity, and the type of treatment (Cordell et al., 2011). For example, anaerobic sludge digestion reduces carbon content and increases phosphorus and cadmium content in sludge. Therefore, average values of phosphorus and cadmium content were calculated for six different types of WWTPs, based on Danish data reporting plant-specific sludge quality for the period 2005–2007 (DEPA, 2009). The other three fertilizer products considered are mineral fertilizer (Sørensen et al., 2011), pig manure from conventional farms (Schwærter and Grant, 2003) and struvite (DEPA, 2013). Fertilizer quality for the nine emission scenarios is reported in Table 1.

Danish regulation establishes for each crop the maximum amount of phosphorus which can be applied yearly to soil via fertilizers (DAFA, 2012; DME, 2006), according to crop-specific phosphorous demands. Three crop-types were considered in this study: cereals, leafy vegetables, and roots, as these are the major contributors to dietary cadmium exposure (Amzal et al., 2009). The application limit of 2200 [$kg_P\ km^{-2}\ year^{-1}$] for cultivation of winter wheat (taken as a proxy for cereals) was used in the study, as this is the lowest limit among the three crop-types.[1]

The application of fertilizer to agricultural soil is modelled as a direct emission of cadmium into a topsoil layer, over a virtual area of 1 km,[2] with a yearly emission rate R_{Cd} [$kg_{Cd}\ km^{-2}\ year^{-1}$] calculated as (1):

$$R_{Cd} = R_P / P_{fert} \cdot Cd_{fert} \tag{1}$$

where: R_P [$kg_P\ km^{-2}\ year^{-1}$] is the limit for spreading of phosphorus, P_{fert} [$mg_P\ kg_{fert}^{-1}$] is the content of phosphorus per dry weight of fertilizer; Cd_{fert} [$mg_{Cd}\ kg_{fert}^{-1}$] is the cadmium content of the fertilizer. For a given fertilizer scenario, R_{Cd} is constant, i.e. it is repeated for each time step of one year, t [year], where $t \in T$, $T = (0, 1, 2, \ldots, 94)$, over the 95 year time horizon.

2.2. Modelling of cadmium fate and exposure

The Simplified Fate and Speciation Model (SFSM) described by Pizzol et al. (2012) was used to model cadmium accumulation in soil. The model accounts for metal speciation and is validated for Danish soil parameters and conditions (pH, organic matter, background metal concentration). The model was set to represent Danish sandy soil with a low concentration of trace elements, as reported in Pizzol et al. (2012).

The *increase* in cadmium topsoil concentration at time t that is attributable to the fertilizer, $\Delta Cd_{soil,t}$ [$mg_{Cd}\ kg_{soil}^{-1}$]; i.e. the topsoil cadmium concentration associated with a value of R_{Cd}, was determined by subtraction of background soil concentration year by year (2):

[1] This choice reflects a precautionary approach, as the application of phosphorus in sludge-derived products is regulated with a higher limit of 3000 [$kg_P\ km^{-2}\ year^{-1}$] or a maximum sludge amendment of 9000 [$kg_P\ km^{-2}$] per each third year (DME, 2006).

[2] FAOSTAT names, respectively: *Cereals – Excluding Beer (Total)*; *Vegetables (total)*; *Starchy roots (total)*.

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