Journal of Cleaner Production 202 (2018) 1107–1119

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Circular economy of composting in Sri Lanka: Opportunities and challenges for reducing waste related pollution and improving soil health

M. Bekchanov*, A. Mirzabaev

Center for Development Research (ZEF), Bonn University, Genscherallee 3, Bonn 53113, Germany

ARTICLE INFO

Article history:
Received 27 February 2018
Received in revised form
30 July 2018
Accepted 18 August 2018
Available online 22 August 2018

Keywords:
Resources recovery and reuse (RRR)
Nutrients recovery
Inter-provincial marketing of the compost
Circular economy
An integrated waste management and fertilizer use model

ABSTRACT

Inadequate management of organic waste is a key cause of environmental pollution and nutrient loss in developing countries. Composting is a win-win option that allows for not only reducing environmental pollution derived by open dumping of waste but also recovering nutrients essential for crop production, consequently enhancing crop yields and reducing expensive chemical fertilizers usage. Considering these environmental and economic benefits, this study develops an economic optimization model to assess the impact and financial feasibility of compost production and marketing in Sri Lanka. The analysis does not treat compost production as an isolated sector, but traces the combined relationship between compost and chemical fertilizer applications for sustainable crop production. The findings indicate that establishing compost facilities to recycle organic waste in Sri Lanka will decrease total waste management and chemical fertilizer use costs by US$191 million. Facilitating inter-provincial trade in compost will further expand the composting potential in the country, reducing waste management and chemical fertilizer use costs by US$357 million. Successful implementation of wide-scale composting projects will require better accounting and planning in the waste management system, greater public awareness about waste derived environmental pollution, and better working conditions and safety in the sector. Increased use of compost in crop production in Sri Lanka depends on improved mechanisms for monitoring and certifying compost quality, more effective compost subsidy policies and increased knowledge and application of Integrated Nutrition Management measures.

1. Introduction

Organic waste and wastewater mismanagement are among the major threats to environmental security and human health in most developing countries (Scheinberg et al., 2010; WWAP, 2017). Lack of investments, inefficient planning, underdeveloped infrastructure, and lack of skilled personnel in the system induce open dumping of waste and exacerbates the environmental pollution. Acute ecological damage and related disease burden due to insufficient investments in waste management and open dumping of vast amounts of organic waste are challenging issues especially in developing countries of South Asia (Visvanathan and Glawe, 2006). Since a large portion of residential waste and wastewater is organic waste which contains essential soil macronutrients such as phosphorus and nitrogen, open dumping of organic waste leaks these nutrients into surface and ground waters, consequently causing eutrophication and disruption of ecosystems. The negative impact of open dumping on the environment also extends to recreational ecosystem services, thus decreasing tourism-based income and economic development (Hernández-Sancho et al., 2015).

Technologies of circular economy approach reduce the leakages and environmental pollution, and lower input uses and costs in the production system by implementing Resource Recovery and Reuse (RRR) measures and recycling the waste (Andersen, 2007; Geissdoerfer et al., 2017). For example, residential wastewater, septage, food waste and manure can be recycled to produce compost which in turn can be applied to agricultural lands to mitigate soil nutrient depletion and land degradation. Through this way, leakage of the nutrients into ecosystems and consequent damage can be prevented and large portion of nutrients extracted from soil by crops and pooled in organic waste and wastewater stocks can be returned to soil. In addition to supplying nutrients,

---

* Corresponding author.
E-mail address: mbekchan@uni-bonn.de (M. Bekchanov).

https://doi.org/10.1016/j.jclepro.2018.08.186

compost improves soil moisture, porosity, structure, texture, cation exchange capacity and water/air infiltration in the root zone. Consequently, nutrient retention in the soil and its intake by crops also get better leading to improved soil fertility and higher crop yields (Samarasinghe et al., 2015). Compost can be used for cultivating all types of crops, including the major crops grown in Sri Lanka such as paddy rice, tea, coconut, rubber and oilseeds. Although compost cannot fully replace chemical fertilizers in the agricultural production systems, it can substitute them to a large extent and reduce overall production costs. Additionally, as global reserves of rock phosphate deplete and chemical fertilizer prices rise, conversion of organic waste into compost may become a more viable alternative (Cordell et al., 2009). Composting can decrease dependence on imported chemical fertilizers and reduce environmental pollution.

This study focuses on the case of Sri Lanka (South Asia) where inadequate treatment of waste and wastewater has increased disease prevalence, environmental pollution and biodiversity loss (UNEP, 2001; Maheshi et al., 2015). Environmental pollution is especially widespread in the highly populated and industrialized municipalities, such as Colombo and Kandy. These cities lack sufficient facilities for appropriate treatment and safe disposal of organic waste and wastewater (Bandara, 2003). Almost 90% of heavily polluted wastewater is dumped into freshwater streams, exacerbating the environmental and human health risks (Sudasinghe et al., 2011). Similarly, uncontrolled dumping of municipal and household waste along the roads, waterways and countryside has negatively impacted living conditions by contaminating potable water sources, polluting soils, increasing disease incidence, blocking waterways and amplifying flooding risks. Although organic waste is currently the root of numerous problems, this waste could be turned into a valuable resource —compost — through recycling. Compost from organic waste can be used as an agricultural input to improve soil productivity, restore degraded lands and reduce chemical fertilizer imports, consequently improving food security.

1.1. Literature review and research gaps

Effective management of waste and compost requires appropriate planning of waste collection, disposal, and recycling while considering the economic feasibility of multiple options along the waste management and crop production chains. Mathematical models are effective tools to enahce decision making on optimal waste management with minimal environmental externalities and management costs. Several modeling approaches including multi-criteria assessment, simulation and optimization modeling have been utilized to analyze various aspects of waste management systems (Juul et al., 2013). For example, Münster and Meibom (2011, 2010) used a linear programming model to identify least-cost technologies to transform municipal solid waste into energy concurrently considering the carbon emission impacts of these technologies. Münster et al. (2015) built upon this model to assess the potential of producing bio-fuel for vehicles, biogas, heat and power from waste. Rathi (2007) applied a linear programming model for assessing possibilities of effectively recycling municipal solid waste into compost and the impacts of production costs on the choice of mechanical and manual composting. Salvia et al. (2002) used linear programming model to analyze the impacts of increased landfilling fees on the choice and adoption of waste recycling options. Mixed integer linear programming models facilitated addressing the complexities in selection of multiple technologies, processes and capacities over long period of time (Shadiya et al., 2012; Tan et al., 2014). Chang et al. (2012) applied mixed integer linear programming model to show the importance of waste recycling to reduce carbon gas emissions. Santibañez-Aguilar et al. (2013) used a similar modeling approach for analyzing costs and benefits under different rates of recycling municipal solid waste. Lee et al. (2016) implemented integer programming approach to analyze the options of transporting municipal solid waste from waste collection points to recycling facilities and the required capacities of incineration plants and landfilling sites. The uncertainties in the municipal solid waste management systems were addressed by Xu et al. (2010) using a stochastic robust interval linear programming model. Tan et al. (2014) developed a multi-annual, mixed integer linear programming model to assess how to optimize selection of the various resource recovery and reuse (RRR) options, including landfill gas flaring, incineration, material recovery facilities, and composting. The model also accounted not only for installation and operation costs but also the impact of harmful gas emissions.

Although all of the described studies made valuable contributions to deepen the knowledge on various aspects of waste management and optimal chocies of recyling technologies, these studies considered the waste management sector in isolation from other related economic activities. Particularly, demand for the commodities produced from waste and impacts of the competing goods were not adequately accounted for. For instance, in the case of recyclign waste into nutrients, prices and efficiency of chemical fertilizers are important factors to determine the demand for compost and the feasibility of waste recycling. Heterogenous demand in compost markets across the provinces also has implications when assessing waste management options and recycling capacities across the provinces and inter-provincial transfer of compost.

1.2. Study objectives and contributions

This study fills the research gaps discussed above by developing an economic optimization model to analyze and compare the costs of open dumping (business-as-usual scenario) and producing compost from organic waste with its subsequent inter-provincial marketing in Sri Lanka. Differing from similar studies that applied optimization models to analyze municipal solid waste management and recycling (Rathi, 2007; Tan et al., 2014), this study analyzes waste management and soil productivity improvement options in an integrated manner. By assessing the optimal balance of chemical and organic fertilizers, this study focuses on the economic feasibility of substitution of chemical fertilizers with compost. In order to account for soil nutrient demand, the model considers nutrient contents of both compost and chemical fertilizers, and the nutritional flows along both food and waste chains. In addition to modeling the role of country-wide composting schemes and inter-provincial trade in compost for environmental sustainability and soil health improvement, the study also addresses the challenges and opportunities for up-scaling compost schemes in Sri Lanka.

The following sections will provide a detailed description of the modelling framework, study area and data collection approaches; present the model simulation results, discussion of the findings and their policy implications; and conclude with recommendations.

2. Materials and methods

2.1. Nutrient routes along waste management and crop production value chains

Modeling nutrients recovery, their distribution and use in the agricultural sector requires understanding how nutrients flow along the food and waste management chains. As shown in Fig. 1,

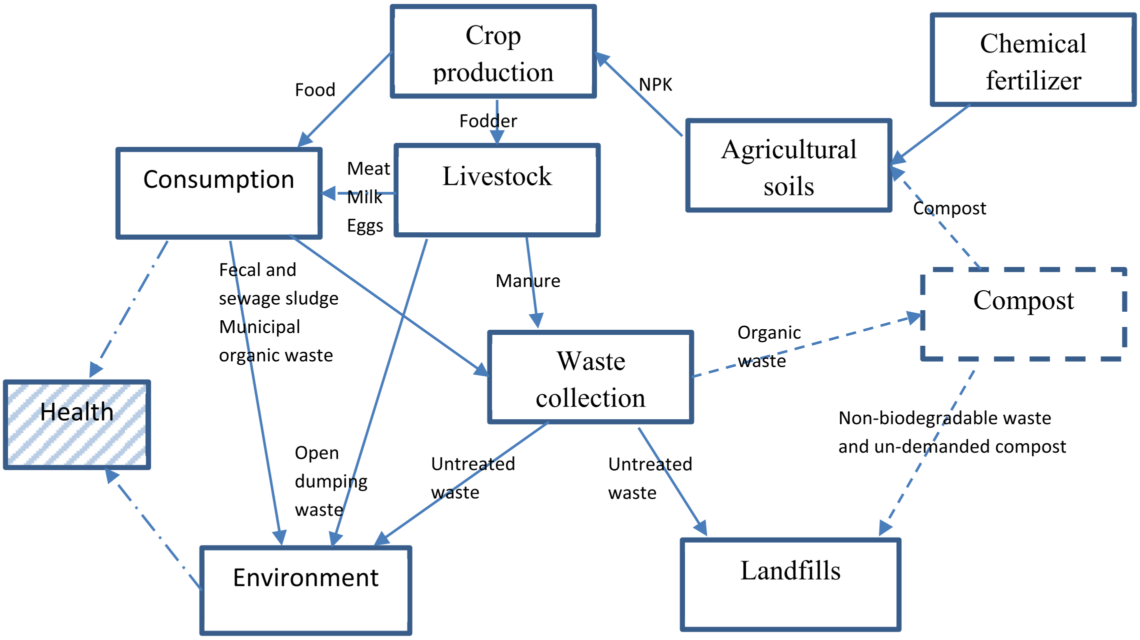

Fig. 1. Routes of nutrient flow along the food and waste management chains.

initially, important macronutrients, such as phosphorus and nitrogen, from the soil are extracted by crops and trees to produce cereals, fruits, vegetables and fodder. Nutrients enter the living bodies through the consumed food and fodder. Harvesting and post-harvest losses as well as food waste during consumption also contain considerable amount of nutrients. A portion of the nutrients embedded in the consumed food and fodder is lost through excretion and pool in wastewater, fecal sludge and manure. In the absence of a functioning waste management system, this biodegradable waste is openly dumped into environment, causing pollution (eutrophication) and health risks. Part of the waste is collected for further treatment or safe disposal into landfills. In systems where there is limited recycling of organic waste or sanitary removal to landfills, most of the consumed nutrients end up in water bodies causing eutrophication. In systems with the availability of composting options, an important share of non-renewable nutrients is returned back to the soil through compost application (except losses through leachate and runoff). Thus, composting organic waste plays a pivotal role to close the nutrients' loop and improve soil health.

In addition to improving soil health, recovering soil nutrients from biodegradable waste can be an effective option for reducing reliance on chemical fertilizer inputs and rehabilitating degraded croplands. Since organic waste and wastewater are largely generated in urban areas but demand for the recovered nutrients is much higher in rural areas with large agricultural production schemes, inter-provincial marketing of the recovered nutrients can improve the feasibility of the composting programs. Thus, effective planning the food and waste management systems would require minimizing the costs of collecting waste, open dumping of waste (environmental pollution externalities), landfilling, segregating waste and composting the biodegradable fraction, and transporting compost. Given the bulky nature of compost compared to chemical fertilizers, its handling and application costs should be also considered. The optimization model described below addresses this cost minimization problem. Based on the conceptual framework described in Fig. 1, the model focuses primarily on recovering nutrients from organic waste to partially substitute non-renewable chemical fertilizers. The model does not consider food availability, nutrient content or the related-health outcomes from improved food security and reduced environmental pollution. In this regard, the model presents conservative estimates of the benefit from compost production and application. The full benefits would also include lower healthcare costs due to decreased environmental pollution.

2.2. Superstructure of the model

The model considers organic waste availability across the provinces of Sri Lanka, and the portions going to open dumps, landfills or compost plants. The model also tracks the uses and distribution of the produced compost across the provinces depending on crop nutrient demand (Fig. 2).

The main organic waste types considered are organic municipal waste, animal waste (cow and buffalo dung, manure of sheep and pigs, poultry litter), sewage sludge (from sewerage) and fecal sludge (from on-site sanitation facilities). Depending on the processing costs and demand for nutrients by the crop production sector, part of the organic waste is processed into compost. The produced compost is applied in combination with chemical fertilizers to meet the nutrient requirements in crop production system. Compost also can be marketed between the provinces depending on its availability, transportation costs and the price of chemical fertilizers (see Annex 1 for model nomenclature).

2.3. Model formulation

The main objective of the model is to minimize the costs of organic waste management (open dumping, waste collecting and sanitary land-filling), composting (compost production, compost transportation and compost application) and supplying chemical fertilizers:

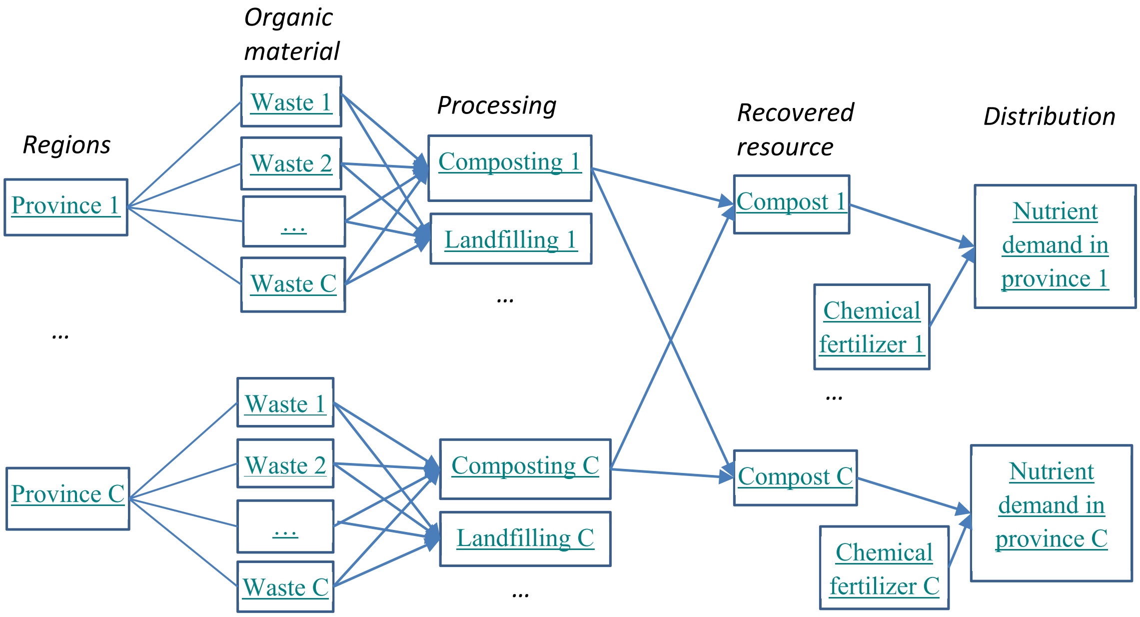

Fig. 2. Superstructure of the model (Authors' presentation).

$$\sum_r\sum_w\left(xp^C_{r,w}\,Q^C_{r,w}+xp^{UC}_{r,w}\left(1-g^{DOM}_{r,w}\right)Q^{UC}_{r,w}+xp^{UR}_{r,w}\,Q^{UR}_{r,w}\right)$$
$$+xp^R_{r,w}\,Q^R_{r,w}+\sum_r\sum_q t_{r,q}\,QM^{TRN}_{r,q}+\sum_r xp^{MUS}_r QM^{USE}_r$$
$$+\sum_r\sum_f p^{FER}_{r,f}\left(1-fert^{SUB}_{r,f}\right)Q^{FER}_{r,f}\rightarrow MIN \qquad (1)$$

where:

$xp^C_{r,w}$ is the cost of collecting waste (type of waste w) in province r (US\$ ton^{-1});
$xp^{UC}_{r,w}$ is the cost of open dumping (US\$ ton^{-1});
$xp^{UR}_{r,w}$ is the cost of land-filling (US\$ ton^{-1});
$xp^R_{r,w}$ is the cost of recycling (composting) waste (US\$ ton^{-1});
$xp^{MUS}_{r,w}$ is the cost of manure application (US\$ ton^{-1});
$g^{DOM}_{r,w}$ is the rate of waste recycling domestically (by households, farms, and hotels);
$t_{r,q}$ is the transportation costs of moving a ton of compost from province r to the province q (US\$ ton^{-1});
$p^{FER}_{r,f}$ is the price of chemical fertilizer (f) in province r (US\$ ton^{-1});
$fert^{SUB}_{r,f}$ is the rate of subsidy to chemical fertilizers [0–1];
$Q^C_{r,w}$ is the amount of waste collected (million ton);
$Q^{UC}_{r,w}$ is the amount of waste uncollected (million ton);
$Q^{UR}_{r,w}$ is the amount of waste unrecycled (million ton);
$Q^R_{r,w}$ is the amount of waste recyclable (million ton);
$QM^{TRN}_{r,q}$ is total amount of compost transferred (exported or imported) from province r to the province q (million ton);
QM^{USE}_r is total amount of compost use in province r (million ton);
$Q^{FER}_{r,f}$ is the amount of chemical fertilizer purchased (million tons).

Organic waste can be collected for further recycling (e.g., producing compost) or disposal into landfills, open dumps or uncontrolled locations. Collected waste ($Q^C_{r,w}$) is considered to be proportional to total amount of waste generated ($qg_{r,w}$):

$$Q^C_{r,w}=qg_{r,w}\,G_{r,w} \qquad (2)$$

where, $G_{r,w}$ is the rate of collecting waste [0–1].

The remaining waste generated is considered as uncollected or openly dumped ($Q^{UC}_{r,w}$):

$$Q^{UC}_{r,w}=qg_{r,w}\left(1-G_{r,w}\right) \qquad (3)$$

A certain portion ($C_{r,w}$) of the collected waste ($Q^C_{r,w}$) is recycled (e.g., composted):

$$Q^R_{r,w}=Q^C_{r,w}\,C_{r,w} \qquad (4)$$

where $C_{r,w}$ is the rate of recycling collected waste [0–1] and $Q^R_{r,w}$ is the amount of waste recycled (million ton).

Thus, the collected but unrecycled waste (dumped into landfills) is calculated as:

$$Q^{UR}_{r,w}=Q^C_{r,w}\left(1-C_{r,w}\right) \qquad (5)$$

where $Q^{UR}_{r,w}$ is the amount of waste unrecycled (million ton) and $Q^C_{r,w}$ is the amount of waste collected (million ton).

The part of the collected waste can go to composting plants. The mass of the compost produced from waste type w ($QM_{r,w}$) is assumed to be proportional to the total amount of the recycled waste ($Q^R_{r,w}$):

$$QM_{r,w}=f^{CON}_{r,w}\,Q^R_{r,w} \qquad (6)$$

where $f^{CON}_{r,w}$ is the coefficient for converting recyclable waste weight into the weight of final product (compost) [0–1].

Consequently, the total amount of compost produced from various types of organic waste in province r is:

$$QM^{TOT}_{r} = \sum_{w} QM_{r,w} \tag{7}$$

where QM^{TOT}_{r} is the amount of total compost produced (million ton).

The share of the compost produced from particular type of organic waste ($SC_{r,w}$) is calculated as:

$$SC_{r,w} = \frac{QM_{r,w}}{QM^{TOT}_{r}} \tag{8}$$

Total available compost in the province considering additional compost trading with the other provinces is calculated as:

$$QM^{USE}_{r} = QM^{TOT}_{r} + \sum_{q} QM^{TRN}_{q,r} - \sum_{q} QM^{TRN}_{r,q} \tag{9}$$

where QM^{USE}_{r} is total amount of compost use in province r (million ton) and $QM^{TRN}_{r,q}$ is total amount of compost exported or imported from province r to the province q (million ton).

To enforce that a particular province either imports or exports compost or does not participate in the compost market at all, the model considers additional trade related constraints:

$$\sum_{q} QM^{TRN}_{q,r} \sum_{q} QM^{TRN}_{r,q} = 0 \tag{10}$$

and

$$QM^{TRN}_{q,r}\, QM^{TRN}_{r,q} = 0. \tag{11}$$

For meeting crop nutrient demands, the total amount of the nutrients available from both organic ($S^{ORG}_{r,k}$) and chemical fertilizers ($S^{NOR}_{r,k}$) should not be less than the total amount of the nutrients demanded by crop production activities in province r ($d^{TOT}_{r,k}$, in 1000 ton). This condition is formulated as:

$$S^{ORG}_{r,k} + S^{NOR}_{r,k} \geq d^{TOT}_{r,k} \tag{12}$$

Furthermore, nutrients available from organic fertilizer uses in each province is estimated as:

$$S^{ORG}_{r,k} = \sum_{w} \left[n^{ORG}_{w,k} \left(\frac{1}{f^{CON}_{r,w}} \right) QM_{r,w} + \sum_{q} n^{ORG}_{w,k} \left(\frac{1}{f^{CON}_{q,w}} \right) SC_{r,w}\, QM^{TRN}_{q,r} - \sum_{q} n^{ORG}_{w,k} \left(\frac{1}{f^{CON}_{r,w}} \right) SC_{r,w}\, QM^{TRN}_{r,q} \right] \tag{13}$$

where:

$n^{ORG}_{w,k}$ is the nutrient (k) content of waste (w) (kg ton^{-1});

$S^{ORG}_{r,k}$ is total availability of nutrients (type k – N,P,K) from organic fertilizer (e.g., compost) (1000 tons);

$SC_{r,w}$ is the share of the compost from waste type (w) in total amount of waste [0–1].

Likewise, total amount of nutrients (k) available from chemical fertilizers ($S^{NOR}_{r,k}$, in 1000 tons) is calculated as:

$$S^{NOR}_{r,k} = \sum_{f} \left(n^{NOR}_{f,k}\, Q^{FER}_{r,f} \right) \tag{14}$$

where $n^{NOR}_{f,k}$ is the nutrient (k) content of chemical (inorganic) fertilizer (f) (kg ton^{-1}) and $Q^{FER}_{r,f}$ is the purchased amount of chemical fertilizer.

The model was designed as non-linear programming (NLP) model with the objective of cost minimization. The model was coded and solved in General Algebraic Modeling System (GAMS) software using non-linear programming solver CONOPT.

2.4. Case study

Given the acuteness of waste related environmental pollution and heavy reliance on chemical fertilizer imports in Sri Lanka, the described model is very relevant to compile recommendations for reducing eutrophication of water bodies and chemical fertilizer import costs in the country. Before discussing the outcomes of the applied model, it is useful to have a detailed insight into waste management and fertilizer supply systems in the study area. Sri Lanka is an island country located in the Indian Ocean (Fig. 3), with a population of approximately 21 million people. The climate is sub-tropical and characterized by hot temperatures and high air humidity. The annual temperatures fluctuate between 24 and 32 °C in the lowlands and 18–27 °C in mountainous zones. Average precipitation is 1674 mm per annum, but the precipitation is spatially and temporally heterogeneous. Heavy rainfall (*monsoon*) occurs between October to March (*maha* season) in the northeast and April to September (*yala* season) in the southwest (Amarasinghe et al., 1999). This variability divides the country to wet and dry zones, where the wet zone receives 2500 and 5100 mm of precipitation annually and the dry zone only 1100–1600 mm

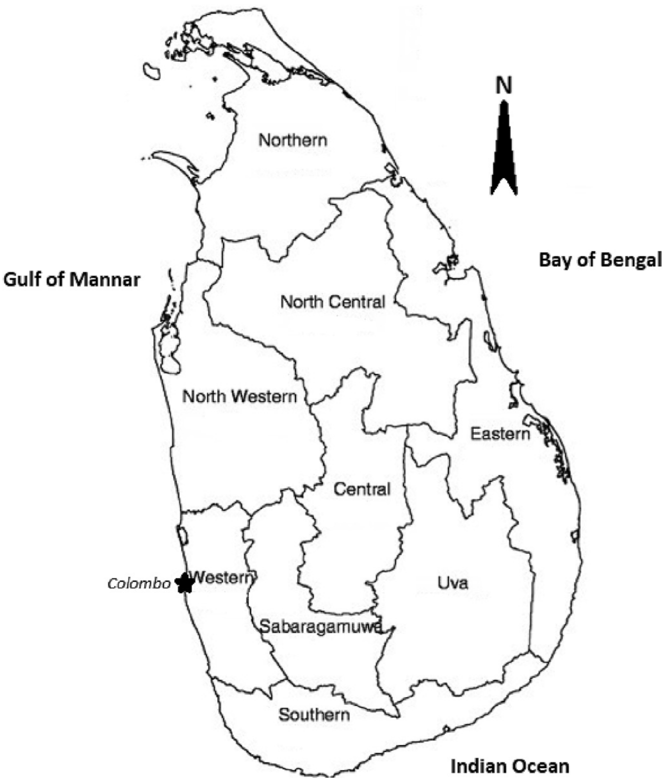

Fig. 3. Provinces of Sri Lanka.

annually.

Agriculture represents about 10% of Sri Lanka's GDP and is an essential source of income for the rural population, which accounts for 80% of population. The sector employs 33% of the economically active population. Of the 2 million ha of croplands available, more than 50% is used to cultivate food crops such as paddy rice (CBSR, 2016). Paddy rice is the most common crop and is cultivated in irrigated systems. Approximately 38% (744 thousand hectares) of the croplands are irrigation-equipped, with 91% of those irrigation-equipped land located in the dry zone (Amarasinghe, 2010). Thus, the dry-zone districts account for 80% of paddy rice production. Cultivation of plantation crops such as tea, rubber and coconut occupies more than 35% of the total cropland and is concentrated in rainfed areas in the wet zone.

Chemical fertilizers such as urea, ammonium sulphate, and superphosphate are commonly used across Sri Lanka to improve agriculture productivity (Weeraratna, 2013). Currently, total fertilizer use is between 600,000 and 800,000 tons per annum (Fig. 4). Urea is the preferred fertilizer, with about 400,000 tons applied per annum. Ammonium sulphate use ranges between 40,000 and 60,000 tons per annum and Triple Super Phosphate between 90,000 and 110,000 tons per annum. Average fertilizer application in cropped areas varies between 300 and 450 kg per ha. Fertilizer use varies between provinces depending on the cropping pattern and total irrigated area. For example, the North-Central Province specialized in paddy rice production is the largest consumer of all types of fertilizers.

The government subsidized the supply of chemical fertilizers over a long period of time to attain national food self-sufficiency, especially self-sufficiency in rice production (Wickramasinghe, 2010). However, chemical fertilizers are largely imported from other countries since Sri Lanka does not have sufficient mineral and ore mines. Despite expensiveness of chemical fertilizer imports, its demand and consumption have been growing. The imports of nitrogen fertilizers increased from 160,000 to 227,000 tons between 2005 and 2014 (Table 1). Similarly, the phosphate fertilizer imports increased from 23,000 to 45,000 tons in this period.

Chemical fertilizer use could be partially substituted by locally produced organic fertilizers given the enormous availability of organic waste generated both in urban settlements and rural livestock rearing systems. Recycling and safe disposal through composting can also reduce the negative externalities of organic waste generating sectors. Considering the multiple benefits of composting, the Sri Lankan national strategy on waste management aims to redirect 19% of the organic municipal waste into compost (Table 2). In districts where agriculture is the backbone of rural livelihoods, such as Kurunegala, Anuradhapura, Polonnaruwa, and Badulla, the targeted rates of waste recycling are higher than in other parts of the country. In 2008, the government introduced the Pilisaru Program, which aimed to establish 110 compost plants throughout the country (JICA, 2013). Currently, most of these

Table 1
Fertilizer production, exports and imports (1000 tons) in Sri Lanka (Based on FAO database).

Year	Production	Exports	Imports
Nitrogen fertilizers			
2005	0.0	0.0	159.6
2010	0.0	0.0	166.1
2014	0.0	0.0	227.4
Phosphate fertilizers			
2005	11.0	0.0	22.6
2010	10.0	0.0	40.7
2014	1.0	0.0	45.4

Table 2
Organic municipal waste collection and composting rates across Sri Lanka (Based on Central Environmental Authority).

Provinces	Organic waste collection (tons per day)	Number of compost plants	Targeted waste recycling (tons per day)	Targeted waste recycling share (%)
Northern	79	3	11	14.0
North-Central	82	16	59	70.9
North-Western	201	21	118	58.7
Central	315	0	30	9.5
Western	1783	17	117	6.6
Southern	250	24	94	37.7
Sabaragamuwa	154	8	36	23.5
Uva	111	7	56	50.6
Eastern	279	6	22	7.9
Sri Lanka	3424	119	657	19.2

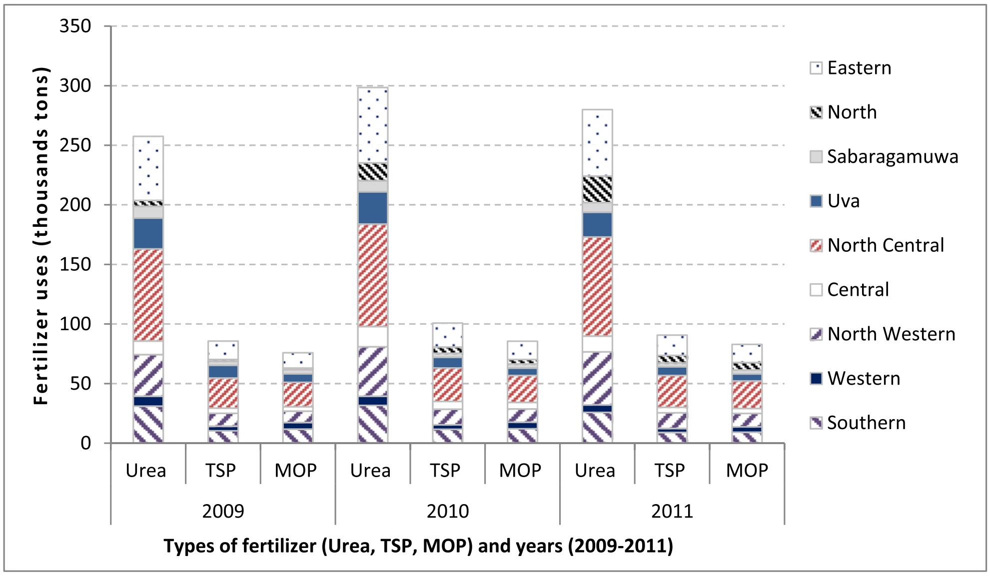

Fig. 4. Fertilizer uses by provinces of Sri Lanka (Based on Weeraratna (2013)).

composting plants have been built and additional plants in some provinces are under construction.

2.5. Data collection

The data on organic waste availability and chemical fertilizer supplies described in the previous section were used to calibrate the optimization model on nutrient recovery from organic waste, along with other data on the scope and cost of operations along waste management and crop production chains. Additional data on population density, cropland areas, and livestock composition across the provinces of Sri Lanka was obtained from multiple statistical and governmental agencies (CBSR, 2016; DCS, 2015, 2012). Gamage et al. (2009) provided data pertaining to the amount and nutrient concentration of manure generated per head of livestock. Data on the content and collection rates of municipal organic waste was available from the reports of the previous studies (JICA, 2013, 2006). Cordell et al. (2009) published figures on the residential sewage waste per capita and its nutrient content. The economic costs of waste collecting, sanitary landfilling, composting and open waste dumping, including environmental externalities, were calculated based on figures generated by Hernández-Sancho et al. (2015) and Rathi (2007; See also Annex 2 for a detailed presentation of the values of the parameters considered in the model).

In addition to quantitative modelling, the study qualitatively evaluated diverse institutional, technical and organizational barriers and opportunities for composting development in Sri Lanka. For this purpose, a field visit was conducted to the composting facilities, where focus group discussions were held with both management and employees of composting facilities. In addition, expert discussions were conducted with key stakeholders in the government, academia, and civil society. These interviews helped compile information and stakeholder views on the financial feasibility, environmental externalities, and socio-institutional challenges and opportunities for up-scaling RRR options in Sri Lanka.

3. Results

Three modelling scenarios were conducted to compare waste management options and analyze potential advantages of compost production from organic waste:

1) No waste recycling (Scenario 1);
2) Composting organic waste without inter-provincial trade in compost (Scenario 2);
3) Composting organic waste with inter-provincial trade in compost (Scenario 3).

Scenario 1 serves as a baseline where all organic waste is openly dumped into waterways, countryside, roadways, or landfills. This scenario matches with the situation in the period before the promotion of composting plants state-wide. Scenario 2 simulates the case where the government supports waste recycling by establishing compost plants across the provinces, but without marketing the compost between the provinces. Farmers have an option of using both chemical fertilizer and compost to meet crop nutrient demands. This scenario matches with the current situation of state-wide government support of recycling organic waste into compost. In addition to producing compost from organic waste, scenario 3 allows for marketing the compost between provinces of Sri Lanka. Thus, the compost producers in urbanized provinces where waste generation rates are higher, such as the Western Province, can sell the extra compost produced to rural provinces with high fertilizer demand. This scenario matches with the possible future when marketing the compost between the provinces is allowed.

The results show that under Scenario 1, the amount of organic waste left uncollected or openly dumped was higher than Scenarios 2 and 3 (Fig. 5). In the Western Province, the amount of organic waste to be recycled is much higher than in the remaining provinces. Until recently, waste was openly dumped along the roads or waterways in most of the rural areas, but was collected in majority of urban areas and deposited either in open dumps or landfills. As

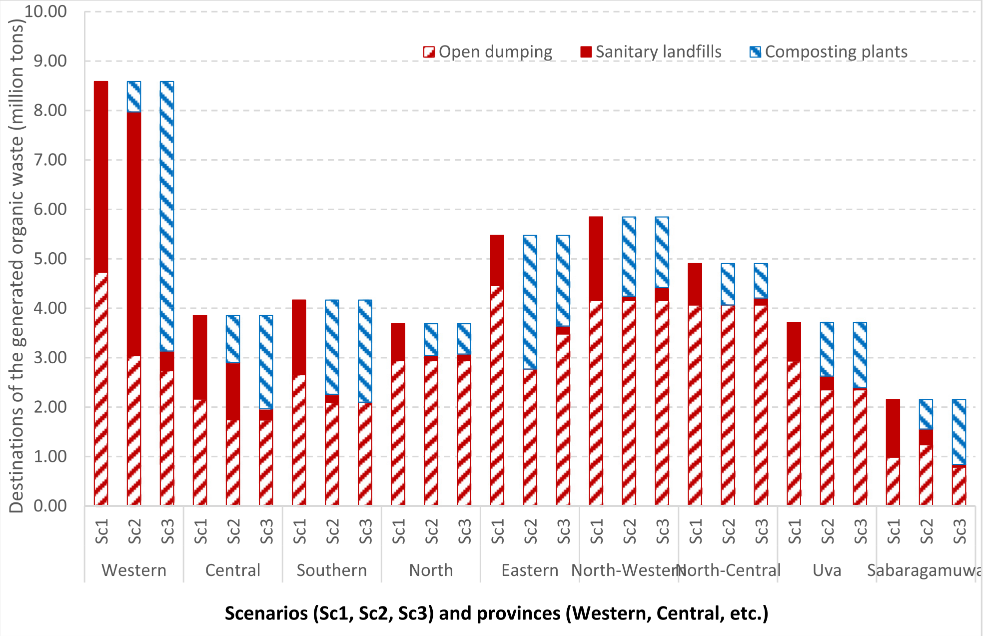

Fig. 5. Organic waste allocated to open dumping, sanitary landfills and composting (Sc1 – 'No waste recycling'; Sc2 – 'Introducing waste recycling targets without the possibility of inter-provincial marketing of the compost', Sc3 – 'Waste recycling with the possibility of marketing of the compost between provinces).

mentioned above, a number of compost plants have been recently established throughout the country with government support. As the modeling results indicate, the promotion of composting (Scenario 2) and increased demand for compost in crop production created strong incentives to collect organic waste and thus reduced the amounts of openly dumped and uncollected waste. In Southern, Eastern, North-Western, Uva and North-Central Provinces, almost all of the collected waste is expected to be recycled into compost due to high demand from agriculture. In the Western Province, despite the availability of vast amount of waste, relatively small agricultural demand for compost constrains composting expansion. Allowing for the trade of compost between provinces (Scenario 3) would substantially increase the rate of organic waste collection and recycling in the Western Province since the produced compost in urbanized provinces could be delivered to provinces with larger cropped areas and with higher demand. Thus, the supply of 657,000 tons of compost from the Western Province to other provinces becomes more cost effective than purchasing chemical fertilizers that contain equivalent amount of soil nutrients. At the same time, the farming areas in the North-Central and Eastern Provinces are expected to be the main buyers of the compost. Increased compost use could reduce the dependence on imported chemical fertilizers. Given the abundance of organic waste for producing compost using internal organic waste, Uva Province is expected not to participate in the inter-provincial trade in compost.

The analysis of the nutrient content of compost shows farmers' dependence on chemical fertilizers in the absence of waste recycling incentives or other government support (Fig. 6). In the absence of composting plants (Scenario 1), households may only produce small amounts of compost in their gardens to implement in few crops or trees. Establishing large-scale facilities for recycling organic waste and composting would require governmental financial support. Large-scale composting also could reduce per unit costs of compost production due to economies of scale. Cheap and good quality compost in massive amounts would expand compost application by farmers. With the increased incentives for recycling waste and composting (scenario 2), the application of organic waste is expected to increase in all provinces. In certain provinces with limited availability of organic waste, such as the North Central province, compost production is expected to be limited and chemical fertilizers would continue to predominate in the agriculture production systems. The possibility of inter-provincial trade in compost (Scenario 3) would benefit the agricultural provinces such as the North-Central Province where farmers could replace, to a large extent, chemical fertilizers by compost produced in other provinces. With the possibility of selling the compost, the compost producers in the Western and Central Provinces could also find new markets in other provinces with high demand for compost and thus increase their profits.

Overall, waste management and fertilizer costs under the three alternative waste management scenarios would be US$ 1.76, 1.57, and 1.4 billion, respectively (Fig. 7). Open dumping of organic waste and lack of recycling (Scenario 1) is the most expensive option because of the long-term impact on the environment (eutrophication) and resulting externalities. Large amount of expenditures is also required to collect waste, maintain sanitary landfills and purchasing expensive chemical fertilizers under this scenario. Recycling a portion of the organic waste into compost (Scenario 2) increases the costs given the construction and operation costs of the compost plants as well as the costs of the compost application. Yet, the environmental pollution costs are reduced due to lower amounts of waste openly dumped or delivered into sanitary landfills. Given the increased use of organic fertilizers, the expenditures for procuring chemical fertilizers are expected to decrease from US$159 million to US$55 million. Inter-provincial trade in compost (Scenario 3) increases compost uses and thus further reduces the environmental pollution (open dumping) and landfill maintenance costs. The costs of the compost production expansion are compensated through reduced costs for maintaining landfills and decreased use of expensive chemical fertilizers.

4. Discussion

4.1. Barriers for compost production in Sri Lanka

Despite techno-economic feasibility and substantial potential for recovering nutrients as shown by the modeling outcomes and strong governmental support for composting plants across Sri Lanka, many technical, financial and institutional barriers to the expansion of compost production and usage need to be overcome. Particularly, compost plant managers face the challenges related with lack of available land to expand composting plants, dumping

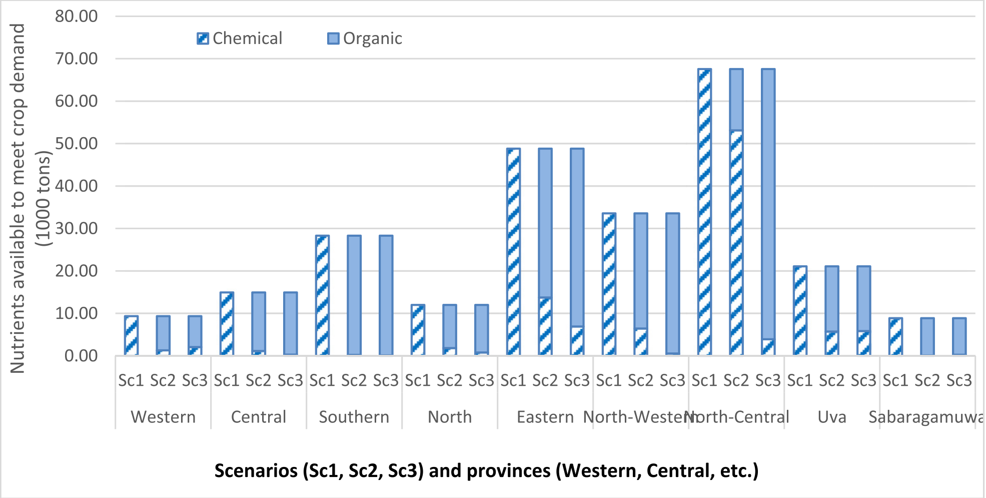

Fig. 6. Total amount of nutrients (NPK) available to meet crop demand and embedded in the applied chemical fertilizers and compost under three waste management scenarios (Sc1 – 'No waste recycling'; Sc2 – 'Introducing waste recycling targets without the possibility of inter-provincial marketing of the compost', Sc3 – 'Waste recycling with the possibility of marketing of the compost between provinces).

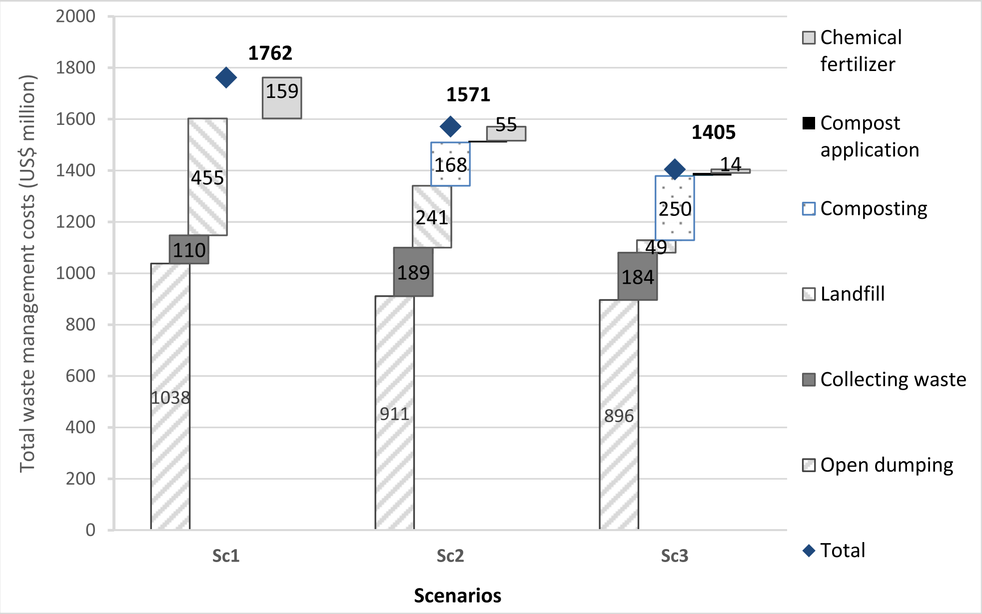

Fig. 7. Total waste management costs under three waste management scenarios (Sc1 – 'No waste recycling'; Sc2 – 'Introducing waste recycling targets without the possibility of inter-provincial marketing of the compost', Sc3 – 'Waste recycling with the possibility of marketing of the compost between provinces).

of the unrecyclable waste, and bureaucratic difficulties in obtaining appropriate land use permits (Samarasinghe et al., 2015). The gap between the laws and their implementation also hampers wider implementation of composting projects.

Complaints over malodor and leachate can escalate to public protests from communities residing near compost plants, despite high quality compost production and market success (Samarasinghe et al., 2015). This suggests that improved site selection and technological improvements, particularly in the production process to reduce malodor, are required to ensure success.

Lack of sufficient funds, low subsidy rates and poor marketability of low quality composts reduces the economic feasibility and hinders composting activities in Sri Lanka. Barriers to proper composting include lack of skilled staff, delivery of mixed waste, lack of improved waste separation technologies and inefficient facility unsuitably designed for local conditions. Local weather conditions, such as the monsoon season with heavy rain, hamper the composting process and reduce efficiency. Production of compost with proper quality requires certain knowledge and equipment to produce compost effectively and efficiently. If improperly treated, pathogenic microorganisms, toxic matter, broken glass and heavy metals existed in compost at higher levels than the allowable can be hazardous to customers. Contamination with hazardous matter and high levels of sand content also reduce the effectiveness of compost for agriculture purposes. Thus, it comes as no surprise that low-quality producers often lose their customers.

The visible effect of compost application on crop growth also takes longer than chemical fertilizer. Commercial farmers may prefer the application of chemical fertilizers due to the immediate and strong effects of chemical fertilizers on crop growth and yield (based on private communications with several compost production experts, 08.08.2016). The bulk mass of compost also increases the transportation, application and labor costs making it less attractive than chemical fertilizers (Samarasinghe et al., 2015). Artificially reduced prices of chemical fertilizers through providing government subsidies also substantially decrease the marketability of composts (Wickramasinghe, 2010).

In addition to external competition, the composting sector also suffers from internal management issues. Low salaries, limited promotions and poor social status reduce willingness to work in the composting sector (based on private communications with composting sector experts, 08.08.2016). Especially finding the skilled workforce required to run the plant and maintain the quality of the compost is very difficult. Therefore, composting plants attract poor segments of the population that are unable to find other work opportunities in urban areas or non-farming sectors.

4.2. Options for improving the compost production and marketing system

In order to upscale composting projects, first comprehensive accounting and planning of the waste and wastewater management system are essential. Historically, waste management systems have not been priorities in the governmental policy agenda, resulting in the underdevelopment of environmental accounting and aggravation of pollution. Given the high costs and low private profits from waste and wastewater recycling despite the many positive social externalities (e.g., improved health and sanitation), government remains as a key actor for supporting the recycling programs. Increased rates of on-site recycling could considerably reduce waste collection and recycling costs. Moreover, raising the awareness of people on environmental benefits of recycling is important for involving a wider groups of the society in the environmental safeguarding.

Social acceptance of composting projects and thus the prevention of the possible public unrest will require improving both the technical process and environmental sustainability of the system. Proper measures of environmental pollution control, including dust control, leachate storage, and adequate ventilation, should be considered during planning and implementation phases. Improved salaries and mechanization of the processes may help not only improve labor productivity and perception of the industry, but also address labor shortage problems. Mechanical sorting facilities at the gates of compost plants should be installed to reduce inorganic matter in the waste, consequently contributing to the improvement of the compost quality.

Enhancing compost quality by controlling sand content, eliminating harmful elements and increasing nutritional value improves the marketability of compost. The control and certification of compost by trusted state organizations is essential to ensure quality and gain consumer trust (Samarasinghe et al., 2015). Grading compost quality and providing information on its suitability to particular crops will increase compost demand. Organizing online platforms for compost marketing where farmers can find information on the quality, quantity and cost of compost can reduce information asymmetry and facilitate wider uses of compost.

Given the extra supply of the compost producible through recycling waste in urban areas, the transportation of the recovered nutrients to the areas specialized in farming can largely contribute to improve soil quality and prevent land degradation in these rural provinces. Inter-provincial marketing of the compost would considerably decrease the reliance on chemical fertilizer uses, resulting in cost savings. The inter-provincial marketing of the compost can be especially effective when the costs of transportation are lower. For instance, using railways or waterways (sea) for transporting compost can be cheaper than the transportation by trucks when complex landscapes and heavy traffic problems are considered.

If chemical fertilizers are heavily subsidized (up to 90% in the recent past), compost use can be economically unviable. The elimination or reduction of government subsidies for chemical fertilizer will improve the demand for compost. In fact, because of the multiple environmental benefits of composting, subsidies can be increased for compost production and organic farming. Improved marketing of organic crops in foreign markets will also increase the economic feasibility of compost use in agriculture. Furthermore, long-term contracts to purchase the compost by agricultural producers may enhance the stability of the composting projects.

Despite increased need and effectiveness of organic compost, it cannot fully replace the use of chemical fertilizers in crop production. However, organic compost should be seen as an essential complement to improve nutrient retention in the soil, increasing element uptake by crops. Thus, Integrated Plant Nutrition Systems should be introduced to promote the application of organic and chemical fertilizers in an optimal ratio to enhance crop yield and improve fertilizer use efficiency (Wickramasinghe, 2010).

4.3. Perspectives for future research

The presented findings have several caveats due to the challenges of covering all the relevant aspects of composting activities in Sri Lanka in a single analysis. The model only considered environmental pollution effects (eutrophication) due to open dumping of organic waste and the consequent leakage of nutrients. The emission of toxic and greenhouse gases due to open dumping and reduction of air pollution due to improved sanitation and waste management should be additionally addressed for in the future studies to assess the role of composting in climate change mitigation. As composting expands and open dumping decreases, the impact of more employment opportunities in composting businesses and the tourism sector, due to the improved natural landscape, should also be included in the analysis. The agricultural component of the model could be further improved by considering relationships between crop nutrient consumption and crop yields, thus identifying the link between food availability, food security and nutrient recovery. Improved food security and decreased environmental pollution has known health benefits which should be included to improve the estimation of benefits from effective waste management. Since demand for organic food is also increasing globally additional revenues from exporting agricultural commodities grown using organic fertilizer could be taken into account in the modeling analyses. In addition to composting, other waste recycling methods, such as producing biogas from organic waste or using wastewater to irrigate non-food crops (i.e., biomass for biofuel or construction materials), should be further investigated. In summary, the results presented here are relatively conservative estimates of waste recycling through composting and subsequent application of compost in agricultural production in Sri Lanka. Even these relatively conservative estimates clearly indicate social viability of expanded waste recycling through composting in Sri Lanka.

5. Conclusions

This study developed an optimization model to analyze organic waste management and soil productivity improvement options in an integrated manner. The findings of the study point to several policy relevant conclusions with considerable implications for sustainable development in Sri Lanka. Firstly, recycling waste and wastewater is a win-win option from both environmental and economic perspectives. Recycling organic waste into compost reduces environmental pollution costs related to open dumping and decreases land requirements for sanitary landfilling. Options for recovering soil nutrients from waste are especially important for reducing public expenditures in countries such as Sri Lanka, where waste mismanagement is a challenging issue and all chemical fertilizers are imported. Expansion of compost production and integrated nutrition management (i.e. combining organic and inorganic fertilizers) helps improve soil health and enhance food security in the country. Inter-provincial trade in compost would provide additional revenues to compost users in major urban areas while concurrently providing cheaper organic fertilizers to agricultural production zones of the country. Secondly, in order to realize these benefits, more investments need to be made to improve the waste management system, transportation infrastructure, compost markets and the overall production capacity in Sri Lanka, including both in terms of technologies and knowledge. Furthermore, compost quality monitoring and certification need to be established to reduce information asymmetry, enhance trust between compost producers and users, and facilitate compost markets. Finally, the government need to play a vital role by establishing appropriate institutional regulations, promoting training programs to raise environmental awareness, and providing financial incentives through subsidies to recycling.

Acknowledgements

This study was financially supported by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) through the joint project (PN10200176) of International Water Management Institute (IWMI) and Center for Development Research (ZEF) titled “Research and capacity building for inter-sectorial private sector involvement for soil rehabilitation project (CB4SoilReha)”. The authors are thankful for Dr Mohamed Aheeyar (IWMI), Professor Ben Basnayake (University of Peradeniya), Dr Sudarshana Fernando (IWMI), Dr Herath Manthrithilake (IWMI), Dr Wasanthi Wickramasinghe (MARGA), Mr Aruna Hewage (HARTI) and Dr Wimala Wimaladasa (the Central Environmental Authority) for their invaluable support for collecting information on waste and wastewater management and crop production systems in Sri Lanka.

Annex 1. Nomenclature

Sets

w is type of waste;
r and q stands for province;
f is type of chemical fertilizer;
k is type of nutrients.

Parameters

$xp^{C}_{r,w}$ is the cost of collecting waste (US\$ ton^{-1});
$xp^{UC}_{r,w}$ is the cost of open dumping (US\$ ton-1);
$xp^{UR}_{r,w}$ is the cost of land-filling (US\$ ton-1);
$xp^{R}_{r,w}$ is the cost of recycling (composting) waste (US\$ ton-1);
$xp^{MUS}_{r,w}$ is the cost of manure application (US\$ ton-1);
$g^{DOM}_{r,w}$ is the rate of waste recycling domestically (by households, farms, and hotels);
$t_{r,q}$ is the transportation costs of moving a ton of compost from province r to the province q (US\$ ton-1);
$p^{FER}_{r,f}$ is the price of chemical fertilizer (f) in province r (US\$ ton-1);
$fert^{SUB}_{r,f}$ is the rate of subsidy to chemical fertilizers [0–1];
$qg_{r,w}$ is total amount of waste generated (million ton);
$f^{CON}_{r,w}$ is the coefficient for converting recyclable waste weight into the weight of final product (compost) [0–1];
$d^{TOT}_{r,k}$ is total amount of the nutrients demanded by crop production activities in province r (in 1000 ton);
$n^{ORG}_{w,k}$ is the nutrient (k) content of waste (w) (kg ton-1);
$n^{NOR}_{f,k}$ is the nutrient (k) content of chemical (inorganic) fertilizer (f) (kg ton-1) and $Q^{FER}_{r,f}$ is the purchased amount of chemical fertilizer.

Variables

$Q^{C}_{r,w}$ is the amount of waste collected (million ton);
$G_{r,w}$ is the rate of collecting waste [0–1];
$Q^{UC}_{r,w}$ is the amount of waste uncollected (million ton);
$Q^{UR}_{r,w}$ is the amount of waste unrecycled (million ton);
$Q^{R}_{r,w}$ is the amount of waste recyclable (million ton);
$C_{r,w}$ is the rate of recycling collected waste [0–1];
QM^{TOT}_{r} is the amount of total compost produced (million ton);
$QM^{TRN}_{r,q}$ is total amount of compost transferred (exported or imported) from province r to the province q (million ton);
$QM_{r,w}$ is the mass of the compost produced from waste type w(million ton);
QM^{USE}_{r} is total amount of compost use in province (r) (million ton);
$SC_{r,w}$ is the share of the compost produced from organic waste (w) [0–1];
$Q^{FER}_{r,f}$ is the amount of chemical fertilizer purchased (million ton).
$S^{NOR}_{r,k}$ is total amount of the nutrients available from chemical fertilizers (1000 tons);
$S^{ORG}_{r,k}$ is total availability of nutrients (N,P,K) from organic fertilizer (e.g. compost) (1000 tons);
$SC_{r,w}$ is the share of the compost from waste type (w) in total amount of waste [0–1];
$S^{NOR}_{r,k}$ is total amount of nutrients (k) available from chemical fertilizers (1000 tons).

Annex 2. Values of the parameters used in the applied model

Table A2.1
Total amount of available waste ($qg_{r,w}$, million ton; Assessments based on JICA (2006), Cordell et al. (2009), Gamage et al. (2009), DCS (2012)).

Provinces	Type of organic waste						
	Cow dung	Swine manure	Manure of sheep and goats	Poultry litter	Fecal sludge	Sewage sludge	Organic municipal waste
Western	1.354	0.060	0.018	0.076	3.330	2.946	0.801
Central	1.415	0.006	0.027	0.031	1.454	0.561	0.362
Southern	1.829	0.004	0.010	0.010	1.403	0.646	0.265
North	2.845	0.000	0.070	0.017	0.604	0.021	0.129
Eastern	4.091	0.001	0.049	0.018	0.878	0.255	0.179
North-Western	3.828	0.063	0.049	0.146	1.351	0.152	0.259
North-Central	3.746	0.017	0.038	0.019	0.715	0.227	0.141
Uva	2.663	0.005	0.015	0.006	0.715	0.177	0.134
Sabaragamuwa	0.651	0.004	0.009	0.014	1.092	0.196	0.191
Total	**22.422**	**0.159**	**0.286**	**0.338**	**11.542**	**5.181**	**2.461**

Table A2.2
Total amount of nutrients demanded by crop production system ($d^{TOT}_{r,k}$, 1000 ton; Assessments based on data from National Fertilizer Secretariat (presented in Weeraratna (2013)).

Provinces	Types of nutrients		
	Nitrogen	Phosphorus	Potassium
Western	4.3	1.7	3.3
Central	8.7	3.0	3.2
Southern	15.7	5.3	7.3
North	7.4	2.4	2.2
Eastern	30.4	9.3	9.2
North-Western	20.8	6.1	6.7
North-Central	41.0	12.9	13.6
Uva	13.3	4.1	3.7
Sabaragamuwa	5.2	1.6	2.1
Total	**146.9**	**46.4**	**51.3**

Table A2.3
Nutrient content of organic waste and chemical fertilizers (Based on Rouse et al. (2008), Christenson and Sims (2011) and Weeraratna (2013)).

Type of organic waste and fertilizer	Nutrients		
	Nitrogen	Phosphorus	Potassium
Nutrient content of organic waste ($n^{ORG}_{w,k}$, kg ton^{-1})			
Cow dung	5.4	2.8	2.8
Swine manure	5.6	4.2	8.6
Manure of sheep and goats	9.7	4.9	9.7
Poultry litter	11.9	7.4	5.3
Urine	9.7	2.2	2.0
Feces	3.3	2.2	1.1
Sewage sludge	2.75	0.55	0.28
Organic municipal waste	8.0	6.5	15.0
Nutrient content of fertilizer ($n^{NOR}_{f,k}$, kg ton^{-1})			
Urea	460	0	0
Trisodium Superphosphate	0	460	0
Ammonium Sulphate	206	0	0
Muriate of Potash (MOP)	0	0	600

Table A2.4
Chemical and organic fertilizer use costs (FAO (2015) and assessments based on WRAP (2004)).

Type of fertilizer	Price
Import price of fertilizer ($p_{r,f}^{FER}$, US\$ ton^{-1})	
Urea	290
Trisodium Superphosphate	380
Ammonium Sulphate	250
Muriate of Potash	330
Costs of manure application in field ($xp_{r,w}^{MUS}$, US\$ ton^{-1})	
In Central, Uva and Sabaragamuwa provinces	6
In the remaining provinces	5

Table A2.5
Costs of waste management (US\$ ton^{-1}; Assessments based on Hernández-Sancho et al. (2015) and Rathi (2007)).

Waste management options	Type of waste							
	Cow dung	Swine manure	Manure of sheep and goats	Poultry litter	Urine	Feces	Sewage sludge	Organic municipal waste
Collecting waste	15.0	15.0	15.0	15.0	4.4	22.0	15.0	22.0
Open dumping	50.5	63.0	89.1	121.4	66.6	34.4	18.5	94.1
Composting	29.2	29.2	29.2	29.2	5.84	29.2	29.2	29.2
Landfilling	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2

Table A2.6
Transport costs ($t_{r,q}$, US\$ ton-1; Calculations based on distance between the provinces (https://www.distancecalculator.net/ (13.10.2017)) and cost of transporting a ton of compost over a distance of 1 km).

Provinces	Provinces							
	Western	Central	Southern	North	Eastern	North-Western	North-Central	Uva
Western								
Central	27.2							
Southern	19.4	37.3						
North	50.4	42.7	63.6					
Eastern	50.4	33.4	54.3	41.9				
North-Western	23.3	25.6	38.8	29.5	39.6			
North-Central	31.0	26.4	45.0	19.4	29.5	10.9		
Uva	46.6	27.2	15.5	55.1	24.8	48.9	38.8	
Sabaragamuwa	19.4	25.6	23.3	56.7	54.3	11.6	36.5	29.5

References

Amarasinghe, U.A., 2010. Spatial variation of water supply and demand in Sri Lanka. In: Jinapala, K., De Silva, S., Aheeyar, M.M.M. (Eds.), National Conference on Water, Food Security and Climate Change in Sri Lanka.

Amarasinghe, U.A., Mutuwatta, L., Sakthivadivel, R., 1999. Water Scarcity Variations within a Country: a Case Study of Sri Lanka. International Water Management Institute.

Andersen, M.S., 2007. An introductory note on the environmental economics of the circular economy. Sustain. Sci. 2, 133–140. https://doi.org/10.1007/s11625-006-0013-6.

Bandara, N.J.G.J., 2003. Water and wastewater related issues in Sri Lanka. Water Sci. Technol.: J. Int. Assoc. Water Pollut. Res. 47, 305–312.

CBSR, 2016. Sri Lanka: Socio-economic Data. Data Report. Colombo, Sri Lanka.

Chang, N.-B., Qi, C., Islam, K., Hossain, F., 2012. Comparisons between global warming potential and cost–benefit criteria for optimal planning of a municipal solid waste management system. J. Clean. Prod. 20, 1–13. https://doi.org/10.1016/J.JCLEPRO.2011.08.017.

Christenson, L., Sims, R., 2011. Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. Biotechnol. Adv. 29, 686–702. https://doi.org/10.1016/j.biotechadv.2011.05.015.

Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. Global Environ. Change 19, 292–305. https://doi.org/10.1016/J.GLOENVCHA.2008.10.009.

DCS, 2015. Economic Census for 2013/2014: Final Report for Formal Industries. Colombo, Sri Lanka.

DCS, 2012. Census of Population and Housing 2012. Colombo, Sri Lanka.

FAO, 2015. World Fertilizer Trends and Outlook to 2018. Avialble online at: http://www.fao.org/3/a-i4324e.pdf (accessed on 27.07.2018).

Gamage, D., Gamage, D.V.S.S., Gunaratne, A.N.D., Subsinghe, D.H.A., Perera, B.M.A.O., Puchpakumara, P.G.A., Gajanayaka, S., Seresinhe, T., Pathirana, K.K., 2009. Livestock for Rural Development and Poverty Reduction: Sri Lankan Experience. Colombo, Sri Lanka.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/J.JCLEPRO.2016.12.048.

Hernández-Sancho, F., Lamizana-Diallo, B., Mateo-Sagasta, J., Qadir, M., 2015. Economic Valuation of Wastewater: the Cost of Action and the Cost of No Action. UNEP.

JICA, 2013. Democratic Socialist Republic of Sri Lanka: Data Collection Survey on Agricultural Network and Marketing. Final report.

JICA, 2006. Data Collection Survey on Solid Waste Management in Democratic Socialist Republic of Sri Lanka. Final Report.

Juul, N., Münster, M., Ravn, H., Söderman, M.L., 2013. Challenges when performing economic optimization of waste treatment: a review. Waste Manag. 33, 1918–1925. https://doi.org/10.1016/J.WASMAN.2013.04.015.

Lee, C.K.M., Yeung, C.L., Xiong, Z.R., Chung, S.H., 2016. A mathematical model for municipal solid waste management – a case study in Hong Kong. Waste Manag. 58, 430–441. https://doi.org/10.1016/J.WASMAN.2016.06.017.

Maheshi, D., Steven, V.P., Karel, V.A., 2015. Environmental and economic assessment of 'open waste dump' mining in Sri Lanka. Resour. Conserv. Recycl. 102, 67–79. https://doi.org/10.1016/J.RESCONREC.2015.07.004.

Münster, M., Meibom, P., 2011. Optimization of use of waste in the future energy system. Energy 36, 1612–1622. https://doi.org/10.1016/J.ENERGY.2010.12.070.

Münster, M., Meibom, P., 2010. Long-term affected energy production of waste to energy technologies identified by use of energy system analysis. Waste Manag. 30, 2510–2519. https://doi.org/10.1016/J.WASMAN.2010.04.015.

Münster, M., Ravn, H., Hedegaard, K., Juul, N., Ljunggren Söderman, M., 2015. Economic and environmental optimization of waste treatment. Waste Manag. 38, 486–495. https://doi.org/10.1016/J.WASMAN.2014.12.005.

Rathi, S., 2007. Optimization model for integrated municipal solid waste management in Mumbai, India. Environ. Dev. Econ. 12, 105. https://doi.org/10.1017/S1355770X0600341X.

Rouse, J., Rothenberger, S., Zurbrügg, C., 2008. Marketing Compost - a Guide for Compost Producers in Low and Middle-income Countries. Eawag, Dübendorf, Switzerland.

Salvia, M., Cosmi, C., Macchiato, M., Mangiamele, L., 2002. Waste management system optimisation for Southern Italy with MARKAL model. Resour. Conserv.

Recycl. 34, 91–106. https://doi.org/10.1016/S0921-3449(01)00095-7.

Samarasinghe, G.G.L.W., Bandara, M.A.C.S., Karunarathna, A.K., 2015. Municipal Solid Waste Composting: Potentials and Constraints (No. 174), HARTI Research Report. Colombo, Sri Lanka.

Santibañez-Aguilar, J.E., Ponce-Ortega, J.M., Betzabe González-Campos, J., Serna-González, M., El-Halwagi, M.M., 2013. Optimal planning for the sustainable utilization of municipal solid waste. Waste Manag. 33, 2607–2622. https://doi.org/10.1016/J.WASMAN.2013.08.010.

Scheinberg, A., Wilson, D., Rodic-Wiersma, L., 2010. Solid Waste Management in the World's Cities. UN-HABITAT.

Shadiya, O.O., Satish, V., High, K.A., 2012. Process enhancement through waste minimization and multiobjective optimization. J. Clean. Prod. 31, 137–149. https://doi.org/10.1016/J.JCLEPRO.2012.03.008.

Sudasinghe, M., Galagedara, L., Gunawardena, E., 2011. Performance evaluation of selected sewerage treatment plants in Sri Lanka. Trop. Agri. Res. 22, 154. https://doi.org/10.4038/tar.v22i2.2824.

Tan, S.T., Lee, C.T., Hashim, H., Ho, W.S., Lim, J.S., 2014. Optimal process network for municipal solid waste management in Iskandar Malaysia. J. Clean. Prod. 71, 48–58. https://doi.org/10.1016/J.JCLEPRO.2013.12.005.

UNEP, 2001. Annual Report: Sri Lanka: State of the Environment 2001. Regional Resource Centre for Asia and the Pacific. Pathumthani, Thailand.

Visvanathan, C., Glawe, U., 2006. Domestic solid waste management in South Asian countries – a comparative analysis. In: Paper Presented at 3R South Asia Expert Workshop, 30 August - 1 September, 2006. Kathmandu, Nepal.

Waste & Resources Action Programme (WRAP), 2004. Using Compost in Agriculture and Field Horticulture. http://www.wrap.org.uk/sites/files/wrap/AgCIP1.pdf.

Weeraratna, C., 2013. Fertilizer use in Sri Lanka with special reference to Chronic Kidney Disease of unidentified etiology (CKDu). In: Symposium on "Chronic Disease of Uncertain Origin (CKDu): a Scientific Basis for Future Action" Organized by the National Academy of Sciences of Sri Lanka.

Wickramasinghe, W., 2010. Alternative Approaches to Substitute Chemical Fetilizers in the Food Crop Sector: Integrated Farming System Approach and beyond (No. 04). Working Paper. Colombo, Sri Lanka.

WWAP, 2017. The United Nations World Water Development Report 2017. Wastewater: the Untapped Resource. UNESCO Publishing, Paris, France.

Xu, Y., Huang, G.H., Qin, X.S., Cao, M.F., Sun, Y., 2010. An interval-parameter stochastic robust optimization model for supporting municipal solid waste management under uncertainty. Waste Manag. 30, 316–327. https://doi.org/10.1016/J.WASMAN.2009.10.006.