ENVIRONMENTAL PERFORMANCE OF NEW WASTEWATER AND SLUDGE TREATMENT ROUTES COMPARED TO CONVENTIONAL APPROACHES

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Abstract

The value of life cycle assessments depends on their completeness and on how well the assessment answers the question asked. In the EU project ROUTES several case studies have been performed in order to evaluate innovative wastewater and sludge treatment scenarios against baseline scenarios, in order to understand whether the new ones perform better or worse from an environmental systems perspective and identify the hot spots in the studied systems from where the main environmental pressure originates. The performed LCA study assesses five impact categories, Global Warming Potential, Acidification Potential, Eutrophication Potential, Ozone Depletion Potential and Photochemical Ozone Creation Potential. This article discusses the relevance of the obtained results and identifies further assessments needed in order to provide a solid result.

The study shows that, at present, although a limited number of impact categories are assessed, the studied energy-demanding technologies, like sequential batch biofilm granular reactor and membrane reactor, have a worse overall environmental performance compared to baseline scenarios, and points out electrical efficiency as the main area to put focus on to decrease the overall environmental impact. It also shows that the technologies aimed at sludge quality improvement exhibit a promising environmental performance, but further assessment, including LCA method development, is needed as the studied impact categories do not model the studied system in a thorough way when it comes to comparing agricultural application of sludge and other disposal options.

Keywords

Life Cycle Assessment, LCA, wastewater, sewage sludge, process development

Introduction

The issue of how to dispose of the large volumes of sewage sludge generated in wastewater treatment in an economically and environmentally feasible way is much discussed. Process development of wastewater and sludge treatment processes can have four main focuses, either to increase efficiency, to reduce or stabilize the amounts of sludge that have to be disposed, to improve the quality of the sludge or to maximize the possibility to recover resources in other ways.

Process development intended to improve wastewater and sludge treatment should preferably include environmental systems analysis of the processes under study, to ensure that suboptimisation is avoided. The EU project ROUTES – Novel processing routes for effective sewage sludge management (see Braguglia et al. (2012) for a project description) performs process development in wastewater and sludge treatment in order to improve the sludge disposal situation in Europe. Some of the studied innovative technologies are listed in Table 1, together with their primary aim. As a part of the process development, life cycle assessment (LCA) was made in order to assess the environmental performance of the treatment processes under development compared with baseline scenarios.

Wastewater and sewage sludge treatment has been assessed by LCA in numerous studies. Several studies, among them Johansson et al. (2008) and Lundin et al. (2004), focuses on the final disposal of sludge and compares alternative solutions. Others, as Peters and Rowley (2009), assess process technologies in the WWTP together with end-uses of sludge, as guidance for policy-makers. A number of studies have, as is also done in this study, investigated the potential of new treatment technologies; for treatment of sludge as done by Svanström et al. (2005) or in the waterline as done by Hospido et al. (2012). To compare new treatment routes towards reference/baseline scenarios is for example done by Larsen et al. (2010).

A first LCA was made early on in the ROUTES project in order to assess the potential environmental performance of the studied technologies combined with different final sludge disposal options: landfill, incineration or agricultural utilisation. This paper presents some of the results from this study and discusses them in relation to whether or not the performed LCA answers the questions asked by the project and if not, which challenges that will have to be addressed in order to improve the LCA.

Method

The LCA was performed in accordance with ISO 14040, ISO 14044 and the International Life Cycle Data System (ILCD) Handbook. All parts of the lifecycle of the studied product or service are studied, giving the possibility to identify which parts of the life cycle are the main contributors to the environmental impact in different impact categories.

Definition of goal and scope

The LCA was performed with the goal of assessing the environmental performance of the studied technologies and compare these to baseline scenarios. The LCA also aimed at identifying the potential of the studied technologies in relation to baseline technologies and thereby inform prioritisation of research activities. It also aimed at revealing from which parts of the wastewater's lifecycle that the main environmental load originates, thereby guiding the further process development. The need from the project is thus technology-specific, focusing on the performance of the technologies rather than the sludge end disposal or other parts of the studied system.

The functional unit is the treatment of sludge [and wastewater] produced by a certain number of person equivalents per day, depending on the size of the WWTP in the different scenarios studied (see Table 1).

Table 1: Some of the studied technologies in the ROUTES project and their main aims and WWTP size studied.

Technology	Minimise sludge prod. in waterline	Maximise sludge stabilisation	Extract resources	WWTP size (PE)
Sequential batch biofilm granular reactor (SBBGR)	x			15 000
Membrane bioreactor (MBR)	x			15 000
Biological treatment with oxic-anoxic cycles	x			30 000
Sequential anaerobic-aerobic digestion		x	x	70 000
Sludge separation (primary sludge: wet oxidation, secondary sludge: sonolysis or ozonation and sonication, hydrolysis or anaerobic/aerobic digestion)		x	x	500 000
Hydrodynamic cavitation and two-stage anaerobic digestion		x	x	500 000
Ammonia stripping			x	70 000
Co-digestion of sludge and organic waste			x	500 000

A general flowchart of the studied systems can be seen in Figure 1. The wastewater enters the system as it enters the wastewater treatment plant (WWTP). The sizes of the WWTPs in the studied scenarios varies, as does the effluent demands, but for each studied innovative scenario, a baseline scenario with the same preconditions was modelled by the project. The WWTPs were designed based on obtaining the same effluent quality.

The studied technologies have three different aims (see Table 1). The technologies developed in order to minimise the generation of sludge in the water line are applied to WWTPs generating sludge not suitable for agricultural use. Both innovative and baseline scenarios were modelled with either landfill or incineration as final sludge disposal. The scenarios aiming to maximise sludge stability aim to enable agricultural application, which is why the innovative scenarios include agricultural use of sludge while the baseline scenarios include incineration or landfill. For the technologies aiming for resource recovery from the sludge, the studied scenarios were compared for landfill, incineration and in some cases agricultural use as sludge disposal.

Production of inputs to the system, such as electricity, heat and chemicals and transportation of sludge between WWTP and sludge disposal site are included in the studied system, but the transport of the input materials is disregarded. System expansion is used in order to avoid allocation for products produced within the system, an approach commonly found in the literature for similar studies (see eg. Johansson et al. (2008) and Lundin et al. (2004)). Production and maintenance of goods, like buildings and machinery, were not assessed.

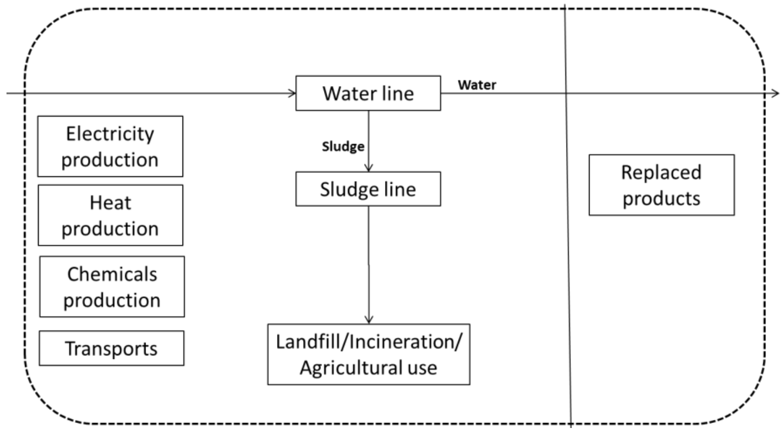

Figure 1: General flowchart of the studied scenarios.

Biogas produced in anaerobic digesters is assumed to be used for internal purposes in the WWTP, such as being combusted in order to preheat digester inflows. In some of the innovative scenarios, both electricity and heat is generated from the combusted biogas. The electricity is considered to be used internally in the WWTP.

Five impact categories were chosen for the life cycle impact assessment (LCIA): global warming potential (GWP), eutrophication potential (EP), acidification (AP), ozone depletion potential (ODP) and photochemical ozone creation potential (POCP). The categories were chosen based on a literature review identifying normal practice (see for example Peters and Rowley (2009) and Svanström et al. (2005)), consideration of the primary interests of project stakeholders and what could be feasibly assessed with available inventory data. The characterisation was made using CML 2001 (2010).

Life cycle inventory (LCI) data was obtained from project partners and literature sources. For the foreground system - the processes that can be directly affected by choices made in the project (wastewater and sludge treatment) - primary data from project partners was preferred. Secondary data was used for the background system and for the foreground system when no primary data was accessible. The study was made for present technology level but, due to that some of the studied technologies are still immature, calculated data have been used in several cases. The study was including emissions to air from the sludge and water lines at the WWTP.

Data on agricultural use of the sludge includes leakage of nitrate from the fields (10% assumed, based on literature review by Svanström et al. (2004)) as well as air emissions of methane, nitrous oxide and ammonia. The sludge is assumed to replace the mineral fertilizers calcium ammonium nitrate and super triphosphate (data from Davis and Haglund (1999)) at a rate of 40% for the N-fertiliser and 70% for the P-fertilizer (Lundin et al., 2004). Landfill modelling considered emissions to air. Incineration was assumed to be on-site mono-incineration and considered emissions to air, with natural gas as additional fuel if such was needed.

Electricity and heat used is modelled as average EU-27 consumption mix, using data from Gabi Professional database (PE International 2011). In innovative scenarios where excess amounts of electricity and heat are produced, this energy was assumed to be recovered and sold. For baseline scenarios, excess energy was not assumed to be recovered. Sludge used on agricultural fields was assumed to replace the production and use of mineral fertilisers. The ammonium sulphate produced in the ammonia stripping was also assumed to be used for agricultural purposes, replacing mineral fertiliser.

Results and discussion

The quality and the usability of the LCA depend on methodological choices as well as on data quality. This section discusses how well the presented results meet the requirements from the project.

Technologies that aim to reduce sludge generation in the waterline

MBR and biological treatment with oxic-anoxic cycles are two examples of technologies developed to accomplish sludge reduction in the waterline. Figure 2 shows that the overall environmental performance of the MBR scenario is worse than for the corresponding baseline scenario; this result is valid regardless of whether landfill or incineration is chosen as final sludge disposal option. The larger electricity consumption demanded in the MBR scenario is not compensated for by the reduced impact from the smaller amounts of sludge sent for disposal. The results show that electricity consumption strongly affects the environmental performance of an MBR, a finding supported by Hospido et al. (2012) who studied different MBRs under diverse operational conditions and volumetric loading rates, and came to the same conclusion.

The EP results were shown to be heavily dependent on emissions to water in the WWTP effluent for many of the studied scenarios and thereby very similar for the compared baseline and innovative scenarios. This was no surprise since design was based on achieving similar effluent quality. For this reason, EP is not discussed for all scenarios presented in the article.

As electricity consumption was identified to be of such large importance, a sensitivity analysis was performed, in which the source of electricity was varied (average EU-27 mix, average Swedish mix or electricity from coal combustion under Italian conditions). The analysis showed that the modelling of the electricity significantly affects the results and can even change the conclusion drawn for some of the studied technologies. The ODP results were particularly sensitive to the electricity modelling, originating almost completely from a refrigerant used in nuclear power in France and some other countries in the data set on average EU-27 mix. These results are therefore not shown or discussed further in this paper.

Figure 3 shows the results for the biological treatment with oxic-anoxic cycles. In this case, the innovative WWTP is clearly beneficial compared to the baseline one, both when landfill and incineration is considered. The electricity consumption is lower in the innovative WWTP compared to the baseline plant, and this contributes significantly to the positive result for the innovative technology.

Looking at both reported results, it can be concluded that in order to obtain an overall improved environmental performance in the studied innovative scenarios, it is essential that the reduced impact resulting from the smaller amounts of sludge to landfill/incinerate is not made up for by the increased impact from higher electricity consumption by the innovative technology. This conclusion is supported by the results for the SBBGR scenario, which is similar to the results from the MBR scenario, although the SBBGR results are not presented in this article.

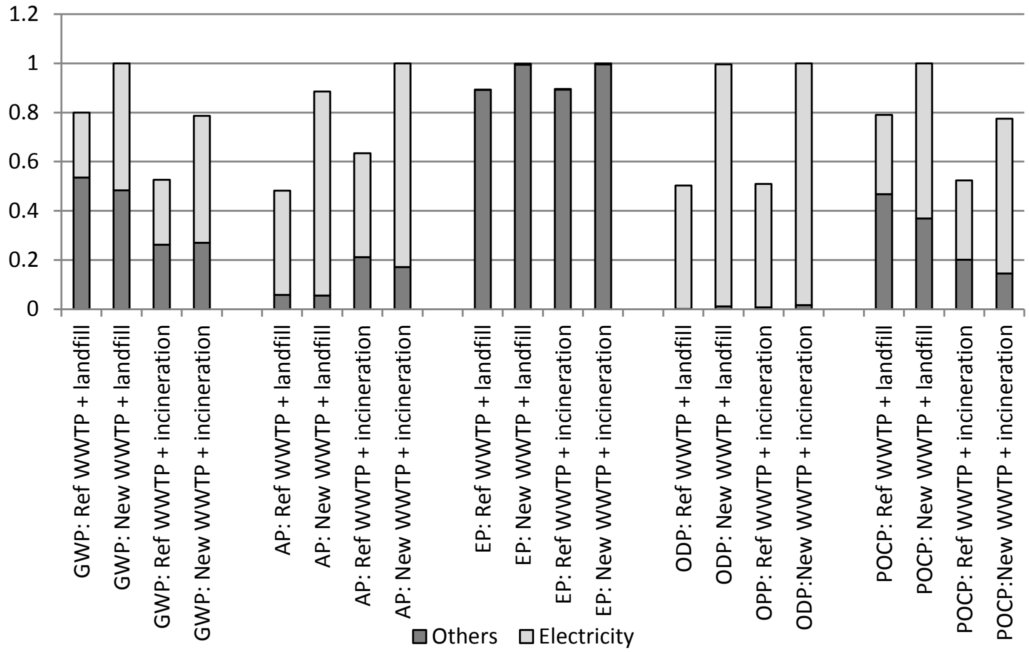

Figure 2: LCIA results for the innovative scenarios that include a membrane bioreactor in order to reduce sludge generation in the waterline, and comparable baseline scenarios.

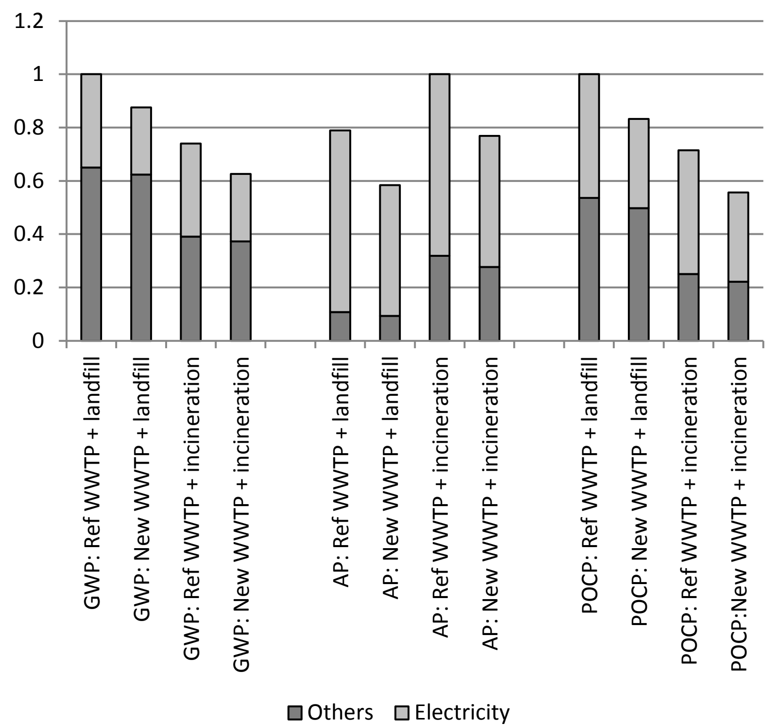

Figure 3: LCIA results for the innovative scenarios that include biological treatment with oxic-anoxic cycles in order to reduce sludge generation in the waterline, and baseline scenarios.

Due to relatively low data quality for landfill and incineration, no comparison is here made between scenarios with different final disposal options. As the need of the project was to be able to judge whether or not the innovative scenario performed better than the baseline scenario, this is thought of as less important. The LCA results are considered detailed enough to draw the conclusion that the MBR scenario is not energy efficient enough to outrank its baseline scenario from an environmental systems perspective, regardless of if the sludge is landfilled or incinerated. The scenario with biological treatment with oxic-anoxic cycles is considered preferable over its baseline scenario. The results also tell us that the main contributor to the overall environmental impact is the electricity production, which enables the project to put effort on decreasing the electricity demand.

Technologies that aim to increase sludge stabilisation and extract resources

The primary interest of the project is to compare innovative wastewater and sludge treatment technologies to baseline technologies, process development aiming at enabling sludge agricultural application puts large requirements on the modelling of the background system. To evaluate if the attempts to maximise sludge stability by the studied technologies are successful from an environmental systems perspective, the LCA needs to be able to assess whether the innovative WWTP in combination with sludge agricultural application is preferable to the baseline WWTP with landfilling or incineration of sludge. This comparison requires the LCA to make a fair comparison between the different sludge disposal options.

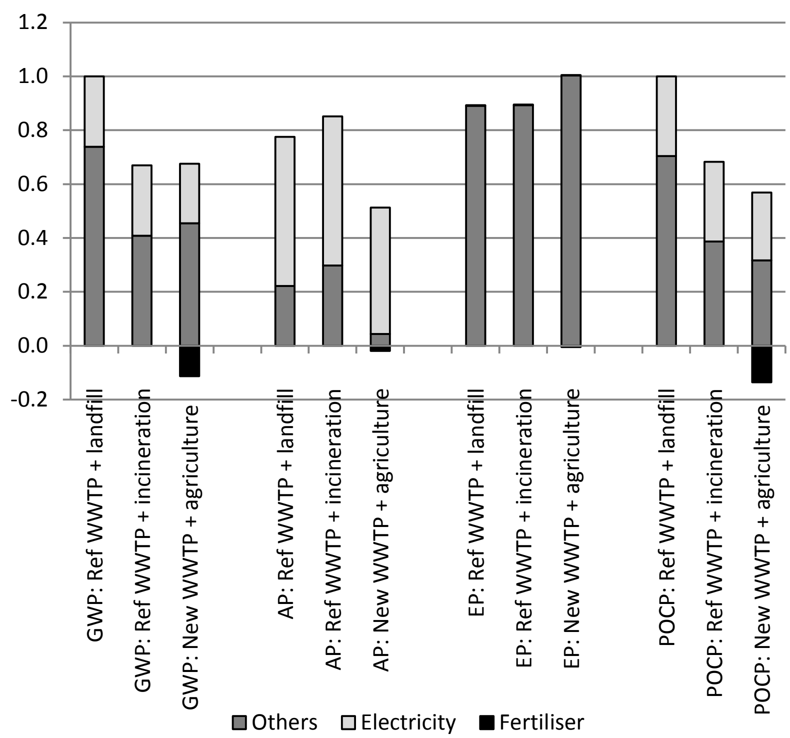

Figure 4: LCIA results for the innovative scenarios that include sequential anaerobic-aerobic digestion in order to improve sludge quality, and baseline scenarios.

Figure 4 shows the results for a technology that includes sequential anaerobic-aerobic digestion compared to a baseline scenario with only anaerobic digestion. As can be seen, the innovative scenario with agricultural use of sludge exhibits a slightly better environmental performance compared to the baseline scenarios for GWP, AP and POCP. For these impact categories, a negative contribution (a benefit) from the avoided production of mineral fertilizer contributes to the results. The difference in EP is mainly due to nitrate leakage from agricultural fields. The results for the scenarios including sludge separation and the ones including hydrodynamic cavitation followed by two-stage anaerobic digestion are not presented in this article but similar conclusions are drawn from these results.

A more comprehensive comparison that includes more impact categories could change the outcome for the studied technologies. The performed LCA does not deal with some important issues such as toxicological effects, odour problems or risks of spreading of diseases connected to sludge agricultural application. These are issues that could potentially contribute to a worse environmental performance of the agricultural scenarios. Hospido et al. (2005) studied anaerobic digestion of sewage sludge in combination with land application and compared to results for thermal treatment and showed that the contribution to human toxicity from agricultural application of sludge is the main contributor to this impact category while thermal treatment results in a negative contribution to this impact category. Peters and Rowley (2009) compared different sewage sludge end-use alternatives (agricultural, landfill and energy recovery in a cement kiln, all after anaerobic digestion) and showed that both human toxicity potential and terrestrial ecotoxicity potential are much worse for the agricultural case compared to the landfill case. However, the actual values reported for these indicators were strongly influenced by assumptions about the soil phase to which the metallic contaminants were bound (see for example Peters et al. (1997)). Furthermore, some potential gains of agricultural application, such as improved soil conditions and carbon content were not assessed. Due to these uncertainties in modelling, the results from the performed study are at this stage considered less valuable for the scenarios aiming at improved sludge quality and need to be complemented with assessments of further impact categories. Additional inventory data is needed in order to assess toxicity. Judgements of impacts connected to odour and risks of spreading of diseases are areas where further development of the life cycle impact assessment method is needed, although some work has been started, see for example Larsen et al. (2009). The question of whether carbon retention in the soil may be considered in cases of agricultural applications, discussed eg. by Peters and Rowley (2009), is relevant both for the assessment of the contribution to climate change and also in relation to potential positive effects on soil quality and moisture retention, which may contribute to improved environmental performance.

The technologies that aim to enable resource recovery

This category includes the technologies discussed in the previous section as all these scenarios are producing and utilising biogas, and are using sludge to fertilise agricultural fields. The study also includes one case study in which biogas is produced from the co-digestion of sludge and organic waste and one in which ammonia stripping is generating the by-product ammonium sulphate.

The scenario in which sludge is co-digested with sludge is modelled with landfill and incineration for both the innovative and the baseline scenario, see Figure 5. The result is beneficial for the innovative WWTP if combined with incineration. For landfill, the results are not as promising for the innovative technology, as could be expected as much larger volumes of digested organic material are landfilled. The results are shown to be dependent on the replaced products, which is why the modelling approach used in these systems is important. The assumption that excess electricity and heat can be recovered and sold determines the outcome.

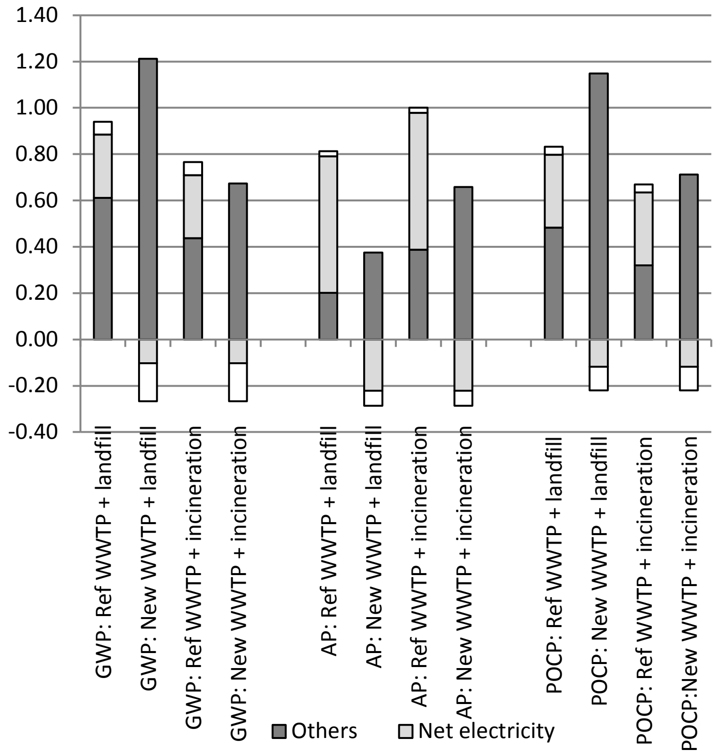

Figure 5: LCIA results for the innovative scenarios that include co-digestion of sludge and organic waste in order to use over-capacity in the digesters to produce excess amounts of biogas, and baseline scenarios, studied for a 500 000 PE WWTP.

Conclusions

- For the scenarios aiming at minimisation of sludge in the waterline and at resource recovery, the LCIA results were considered valuable for deciding on most preferable scenarios, as long as comparisons are made for the same sludge disposal option in compared scenarios. The electricity efficiency of the sludge minimising technologies were essential for the results. For scenarios aiming at resource recovery modelling of the expanded system showed to be important for the results.
- For scenarios aiming at improving sludge quality, results are considered less valuable. In order to improve the modelling of agricultural use of sludge a need for further inventory data collection and LCA method development is identified.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7 2007-2013) under the Grant Agreement n. 265156. The authors would like to thank members of the project ROUTES that have contributed with inventory data, especially Prof Giuseppe Mininni, Prof Giorgio Bertanza, Dr Giuseppe Laera, Dr Matteo Canato and Dr David Bolzonella.

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