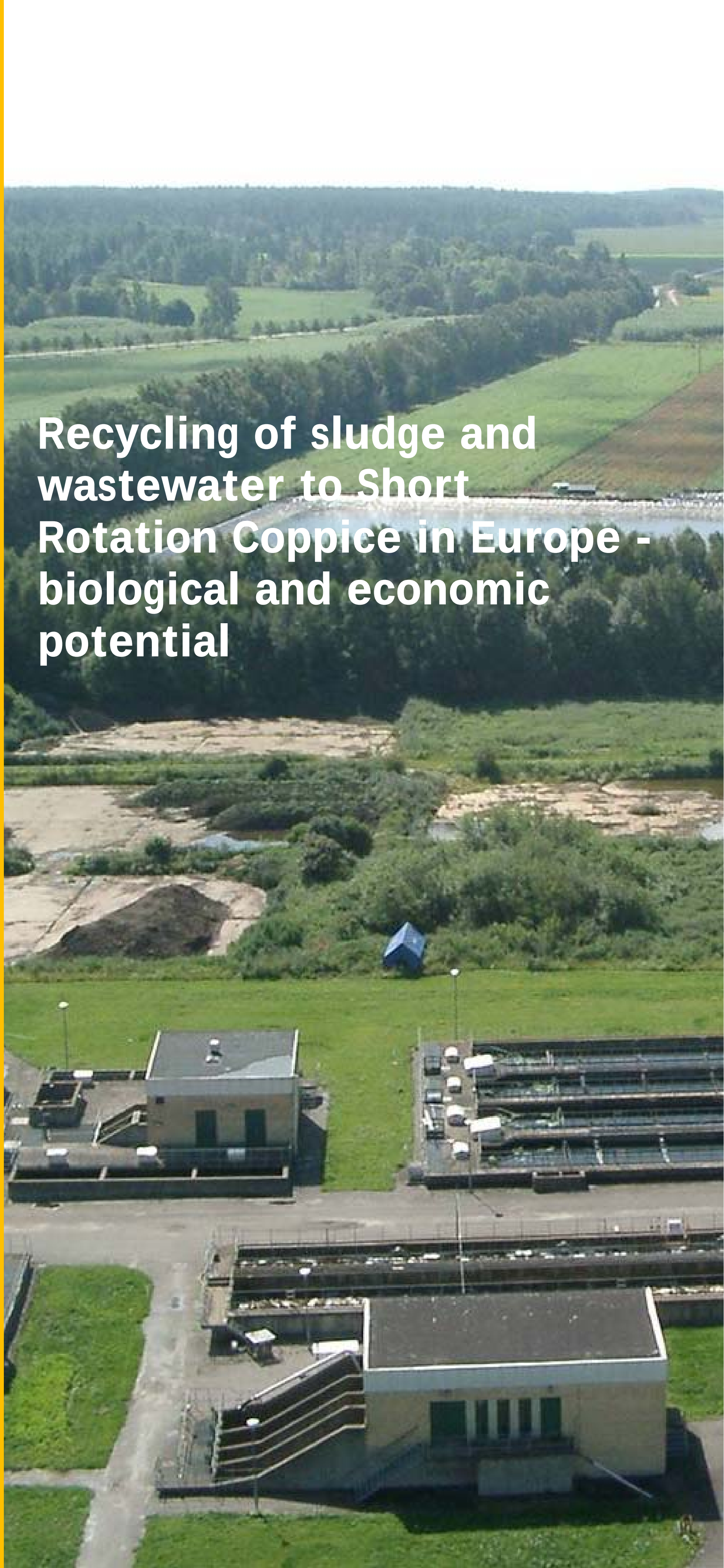
Recycling of sludge and wastewater to Short Rotation Coppice in Europe - biological and economic potential



This report was prepared by Ioannis Dimitriou, Håkan Rosenquist and Pär Aronsson at Swedish University of Agricultural Sciences. The report discusses recycling of nutrient-rich municipal residues to short rotation coppice plantations as an attractive method for attaining environmental and energy goals set for Europe. It is shown how the residues are treated efficiently and the production of biomass for energy is enhanced. The technical potential in EU for this type of residue treatment – if sludge and wastewater availability sets the limit – corresponds to about 6000 PJ of annual biomass production.

IEA Bioenergy

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Recycling of sludge and wastewater to Short Rotation Coppice (SRC) in Europe - biological and economic potential

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KEY MESSAGES

Application of nutrient-rich municipal residues, such as wastewater and sewage sludge, to Short Rotation Coppice (SRC) is among the most attractive methods for attaining environmental and energy goals set for Europe. The method has proved biologically acceptable as a treatment alternative method, since treatment efficiency of N and P is equally high as for other treatment methods. At current woodchip prices in Sweden, the gross margin for SRC cultivation is positive only if biomass production is >9 t DM/ha yr. The gross profit margin increases (by 39 and 199 €/GJ, respectively) if sewage sludge and wastewater are applied to SRC. On top of this, the farmer's profit can be markedly increased if compensation for waste treatment instead of the alternative is attributed to them. The use of more P-rich residues appears more rational since the crop nutrient and water requirements are better met. The technical potential in EU for this type of residue treatment – if sludge and wastewater availability sets the limit – corresponds to about 6000 PJ of annual biomass production.

INTRODUCTION

The term Short Rotation Coppice (SRC) refers to biomass production systems for energy purposes using fast-growing tree species, e.g. willows (*Salix* spp.) in Northern America and Europe, poplars (*Populus* spp.) and eucalyptus (*Eucalyptus* spp.) in more southern climate conditions, having the ability to resprout from their stumps after being harvested at short intervals (2–4 years). Crop management of SRC, such as soil preparation, weed control, planting, fertilisation, harvest, etc., more resembles annual agricultural crops than forestry. SRC is probably the most energy-efficient carbon conversion technology to reduce greenhouse gas emissions (Styles and Jones, 2007) and therefore is considered by several stakeholders as a promising means to contribute meeting European targets for increasing the amount of renewable energy (EEA, 2006; Jordbruksverket, 2006; DEFRA, 2007; Murach et al., 2008).

Despite an expected increase for producing energy biomass on agricultural land in the future, food prices are showing signs of increase and this will result in pressure for more food-crop production on agricultural land. Therefore, future agricultural bioenergy systems should be 'land-efficient', and the amount of energy produced per hectare should be the highest possible. Also, cultivation practices for such systems should be more profitable than those for food crops, to motivate farmers to grow bioenergy crops. To meet all the above, the application of society's residues rich in nutrients, e.g. wastewater or sewage sludge, to SRC plantations has been identified as an attractive method for achieving environmental and energy goals, while simultaneously increasing farmers' income. SRC is a non-food, non-fodder crop that offers advantages such as high evapotranspiration rate, tolerance to anoxic conditions and heavy metals, and therefore is considered appropriate for such applications (Aronsson and Perttu, 2001; Dimitriou and Aronsson, 2005; Rosenqvist and Dawson, 2005; Berndes et al., 2008).

This report will illustrate the biological and economical potential of recycling of sewage sludge and wastewater to SRC, describe a practical example from Sweden where such a system has been successfully established, and investigate implications on a potential increase of SRC if widespread implementation of this system occurs. It should be mentioned that when referring to the current situation of SRC, and when using this system for comparisons, conclusions etc., we refer to the existing situation in Sweden; there, SRC is an established crop with a functioning bioenergy market, and crop management is fully mechanised. In a sense, this illustrates a future possibility in other countries if smooth development of SRC as bioenergy crop takes place.

Figure 1. SRC willow plantation in the landscape.

BIOLOGICAL POTENTIAL

SRC as an agricultural crop needs fertiliser to achieve high biomass production. The use of wastewater and sludge as nutrient sources was investigated in several countries from the early stages of SRC development, as a cheap alternative to conventional fertilisers, and a number of studies indicated the potential of applying wastewater and sewage sludge to SRC to increase the profitability of SRC cultivation by decreasing fertilisation costs and increasing biomass production (Perttu and Kowalik, 1993; Labrecque et al., 1997; Rosenqvist et al, 1997; Guo and Sims, 2001; Rosenqvist and Dawson, 2005). However, the implementation of this treatment option for residues would be valid only if wastewater and sewage sludge applications are conducted in an environmentally safe way, which implies minimum nutrient leaching to or any other negative impact on the groundwater, and soil quality protection. Furthermore, treatment efficiency should be adequate and meet demands by legislation.

Applications of sewage sludge to SRC are strictly regulated and follow the same regulations for sewage sludge application as for other agricultural crops. Therefore, the environmental safety of such a method is ensured by law, and the latest trend to induce stricter regulations for sludge application to arable land based on potential heavy metal accumulation in the soil contributes to higher safety. An advantage of applying sewage sludge to willow SRC is that the amount of Cd supplied with sludge is compensated via uptake in the shoots and consequent harvest of the shoots; therefore resulting in a net reduction of Cd in the soil (Berndes et al., 2004; Dimitriou et al., 2006).

Figure 2. Willow SRC field applied with sewage sludge (Photo courtesy of Urban Eklund)

For wastewater, permission to irrigate SRC is more complex; e.g. in some European countries, natural systems with SRC for treatment of wastewater do not qualify for use (Anonymous, 2009). Often a case-to-case approach occurs, with decision-making usually left to the environmental authorities of each municipality. In Sweden and the UK, however, there are currently c. 10 large-scale SRC systems in operation for treatment and utilisation of wastewater (Dimitriou and Aronsson, 2005; Sugiura et al., 2008), and the method is gaining interest and is planned to be implemented in other countries as well (e.g. Canada – Canadian Forest Service, 2007; Estonia – Aasamaa et al. (2010); India – Pandey and Srivastav, 2010; Italy – Guidi et al. (2008)). The reported treatment efficiency of such systems has been rather satisfactory, despite deviations due to varying local conditions in each area, such as management practices, nutrient loading, soil properties, climate, plant material, etc. Removal rates for N, P and BOD, equal to 82–93, 90–97 and 74–82%, respectively, were reported by Hasselgren (2003) when secondary wastewater effluent (2.45 mg P/l) was applied to SRC at various rates. Dimitriou and Aronsson (2011) found that when willows were irrigated with untreated wastewater (4 mg P/l, 34.7 mg N/l), N retention was 90–96%, and retention of total P was c. 94%, for both willows and poplars irrigated with wastewater in doses corresponding to loads of more than 300 kg N/ha yr and c. 30 kg P/ha yr, which is well above recommended fertilisation rates. Note that the average treatment efficiency for N in Swedish wastewater treatment plants in 2008 was 56%, and for P 95% (SCB, 2010).

Figure 3. Willow SRC field irrigated with municipal wastewater.

ECONOMIC POTENTIAL

To realise the economic potential of applying municipal residues to SRC, it is useful to compare the gross margins of “conventional” SRC management with the corresponding margins when sewage sludge and wastewater are applied. In Table 1, the calculated gross margins for SRC cultivation, for a range of yields and woodchip prices, are illustrated (Dimitriou and Rosenqvist, 2009). The results show that low yield or low woodchip prices result in very low gross margins for SRC cultivation. For example, if a yield of 9 t DM/ha yr is achieved (a ‘satisfactory’ yield for a commercial, well-managed SRC plantation according to Larsson (2001) and Mola-Yudego and Aronsson, 2008)), and the price of woodchips is 5 EUR/GJ (the approximate price for woodchips in Sweden in 2009), the gross margin for 2009 is zero. This means that, without any compensation in the form of subsidies (there is an establishment subsidy of c. 500 EUR/ha), SRC cultivation could not readily be justified.

Table 1. Gross margin of SRC (EUR/ha) for a range of yields and wood chip prices (for Swedish conditions in 2009; 1 MWh = 3.6 GJ, 1 t DM = 15.8 GJ). In: Dimitriou and Rosenqvist (2011).

Price (€/GJ)	Yield level (t DM/ha)							
	5	6	7	8	9	10	11	12
2	-291	-306	-322	-337	-352	-368	-383	-398
3	-226	-228	-230	-233	-235	-237	-239	-242
4	-161	-150	-139	-128	-117	-107	-96	-85
5	-96	-72	-48	-24	0	24	48	72
6	-30	7	44	81	118	154	191	228
7	35	85	135	185	235	285	335	385

In order to calculate potential changes in costs and revenues for SRC cultivation when sewage sludge is used as fertiliser, we need to consider a number of management practices that are affected following such applications. For instance, the permitted amounts of P applied to SRC are, in most cases, more than sufficient for the requirements of SRC. For example, 22 kg of P /ha and year are applied in Sweden to soils with high P content, and 35 kg P to soils with low P content, which may be compared with the annual estimated SRC uptake of 7–10 kg P /ha and year (depending on SRC growth) (Dimitriou, 2005). However, almost equal amounts of N are supplied to SRC, indicating that additional N fertilisation is required if substantial biomass increases are required. From the above, and if we consider current Swedish SRC management practices and an expected yield of 9 t DM/ha yr (the 'normal' expected yield), when sewage sludge is applied, the gross margin for SRC cultivation at a woodchip price of 5 EUR/GJ, increases to 39 EUR/ha (Table 2).

Table 2. Gross margin for SRC cultivation when sewage sludge is applied (EUR/ha) for a range of yields and wood chip prices (Swedish conditions, 1 MWh = 3.6 GJ, 1 t DM = 15.8 GJ). In: Dimitriou and Rosenqvist (2011).

Price (€/GJ)	Yield level (t DM/ha)							
	5	6	7	8	9	10	11	12
2	-263	-276	-288	-301	-313	-326	-338	-351
3	-198	-197	-197	-196	-196	-195	-195	-194
4	-133	-119	-105	-92	-78	-65	-51	-37
5	-67	-41	-14	13	39	66	92	119
6	-2	38	77	117	157	196	236	276
7	63	116	169	221	274	327	380	432

Growth increases of SRC due to wastewater irrigation have been reported in a range of cases (Aronsson and Perttu, 2001; Hasselgren, 2003; Larsson et al., 2003; Sugiura et al., 2008), and higher SRC yield increases are to be expected in drier climates when wastewater irrigation occurs, since SRC has been reported to be water-stressed even in north- European climates (Linderson et al., 2007). Although it is highly variable and site-specific, in this report we assume that an increase in biomass production after wastewater fertilisation can be between 20–50%, although higher increases could be expected in drier climates. In Table 3, the gross margin for SRC cultivation when irrigated with wastewater is illustrated. If we consider a c. 30% yield increase due to wastewater irrigation (which equals c. 3 tonnes DM/yr), the gross margin achieved under Swedish conditions, and at the current approximate price of 5 EUR/GJ, will be 199 EUR/ha (from 0 EUR/ha in Table 1). These cost reductions are a) the result of the biomass increase (for our example 3 t DM/ha leads to a c. 9% of the total costs, and b) the result of the saved cost for fertilisers (due to wastewater irrigation) minus the increased costs (due to yield increase) for harvest, transport of woodchips and brokerage (c. 16% of the total management costs) (Dimitriou and Rosenqvist, 2011). If a greater yield increase occurs where water is a clear limiting factor for growth, e.g. up to 15 t DM/ha yr, the gross margin for SRC would be 294 EUR/ha, which indicates the large potential of wastewater irrigation to SRC plantations.

Table 3. Gross margin for a range of yields and wood chip prices (EUR/ha) for SRC cultivation when irrigation with wastewater occurs (Swedish conditions, 1 MWh = 3.6 GJ, 1 t DM = 15.8 GJ).

Price (€/GJ)	Yield level (t DM/ha)							
	8	9	10	11	12	13	14	15
2	-242	-249	-256	-264	-271	-278	-286	-293
3	-137	-131	-126	-120	-114	-109	-103	-97
4	-33	-14	5	23	42	61	80	98
5	72	103	135	167	199	231	262	294
6	176	221	266	311	355	400	445	490
7	280	338	396	454	512	570	628	686

The economic gains for a farmer growing SRC mentioned above can be further increased if the opportunity costs for handling and distributing the residues as an alternative treatment method are taken into account. Compensation for receiving the wastewater can be up to 1125–2860 EUR/ha yr (Rosenqvist and Dawson, 2005) when 150 kg N/ha yr are supplied to SRC, which is common practice in such systems in operation in Sweden and elsewhere. To estimate the extent of potential compensation to the SRC farmer who applies sewage sludge in Sweden, it is of interest to cite Weglin (2004), who points out that application of sewage sludge to SRC is one of the cheapest sludge disposal solutions for Swedish wastewater treatment plants, with a corresponding cost of c. 22 EUR/t sewage sludge (average of 11 municipalities). For comparison, the cost for the alternative ways of disposing of sewage sludge, such as incineration and landfilling, was c. 60 EUR/t. If we consider that approximately 1 t sludge DM/ha is applied every year to SRC (c. 3.5 t sludge/ha), then the cost to a wastewater treatment plant for handling sewage sludge applied to SRC, is in the range of 77-210 EUR/ha yr. A substantial part of this amount should be available for compensation to the SRC farmer who receives the residues, but the exact amount is rather difficult to identify or predict, since in reality this is the result of an agreement between the potentially involved parties, i.e. the wastewater treatment plant, the companies/entrepreneurs who handle and apply the residues, and the farmer who accepts the residues.

RECYCLING OF MUNICIPAL RESIDUES TO SRC: CASE STUDY ENKÖPING

The following example from Enköping, a city in central Sweden with 20 000 inhabitants where a 75-ha willow plantation is used to treat and utilize decanted water from dewatering of sewage sludge, is presented to explain in more detail how such a system works in reality. This decanted water emanating from dewatering of the sewage sludge produced in the wastewater treatment plant contains approximately 25% of the N entering the wastewater treatment plant, but constitutes less than 1% of the water volume. Thus, by treating this water separately instead of pumping it back into the treatment plant the total nitrogen load is reduced by 25%. The relatively limited water volume (around 25 000 m^3 per year containing some 20 000 kg N and 600 kg P) enables storage in ponds during wintertime, which also is required to reduce the number of pathogens. During the period May-September the water is used for irrigation of the adjacent willow SRC plantation by use of drip pipes laid in every other row (in order not to obstruct harvest machinery). To boost growth and further improve the overall N treatment efficiency of the wastewater treatment plant, the system is designed so that conventionally treated wastewater can be added through the irrigation system. The irrigation load is approximately 250 mm per year resulting in a load of c. 200 kg N and 10 kg P per hectare. Ongoing monitoring has so far shown low N leaching losses, and thus, the system is apparently capable of transforming the large quantities of N added.

The municipality covered all costs for the storing ponds, pumps, automatic filters, and irrigation pipes (which were lower than the estimated costs for improved conventional nitrogen treatment), whereas the farmer/landowner planted the willow SRC field and is responsible for maintenance of the irrigation pipes. The produced biomass is used in district heating plants in the region including the local combined heat and power station of Enköping thereby contributing to the local supply of heat and electricity. The ash from the boiler is then recycled back to the SRC, and thus, the treatment system is an excellent example of how treatment and recycling of society's residues can be combined with production of biomass for energy.

Figure 4. View of the municipal wastewater plant, with water storage ponds and (behind the ponds) the willow fields that are used as vegetation filters. The photo is taken from the roof of the heat and power plant that uses the locally produced biomass.

POTENTIAL FOR SRC AREA INCREASE DUE TO WASTEWATER AND SEWAGE SLUDGE APPLICATIONS

Since P is a limited natural resource which should be recycled, and is usually the limiting factor for maximum application rates of residues, an attempt to quantify the agricultural areas that could be established with SRC if all available P in wastewater and sewage sludge were applied in Sweden and other European (IEA Bioenergy Task 43) countries is made in Table 4. The calculations presented are extrapolated based on the calculations for Sweden, where real data for P in wastewater treatment plants were used. In these calculations it was considered that P after treatment (ending up in treated wastewater) was 5% and P remaining in the treatment plant (P content in sludge) was 95% (similar to the Swedish average for treatment efficiency in wastewater treatment plants for 2006). The theoretical P application rates to SRC were calculated to be equal to crop demand based on the assumption that 0.8 kg P is contained in 1 t DM of harvested willow shoots (Dimitriou 2005). Based on these assumptions, a potential future use of all sewage sludge for application on SRC would theoretically require *c.* 19% of the available arable land in Sweden (*c*. 500 000 ha), which is a substantial area. If calculations were made on the basis that 22 kg P/ha yr can be applied to SRC, then less land (*c.* 7%) would be needed. As regards the potential application of wastewater, the demand on arable land for SRC would be *c.* 0.8% (23 000 ha), but still significant, considering that the current SRC area in Sweden is ca. 12 500 ha. The annual contribution to the energy supply due to SRC biomass if all P from wastewater treatment plants was applied to SRC would be *c.* 110 PJ (ca. 30 TWh, Table 4).

To be more ‘land-efficient’ when recycling P to SRC, wastewater richer in P should be applied. The N/P ratio in wastewater discharged from treatment plants in Sweden is *c.* 50/1 in 2008, (SCB, 2010), and a P-richer wastewater will be closer to the nutrient needs for SRC species willow and poplar (for willow N/P in shoots is 100/14, Aronsson and Perttu (2001)). In the case of a 7-times richer wastewater, the water needs for SRC would also be met: the total volume of treated wastewater produced in Sweden in 2008 was 1.26 x 10^9 m^3 (SCB, 2010) and the theoretical wastewater irrigation rate of all 23 000 ha that would be needed to apply all P to SRC (on the basis of 5% P in wastewater) would be 5480 mm/ha, which is very high. If P-rich wastewater was used for SRC irrigation, the irrigation rate would be *c.* 780 mm which is a rather appropriate amount for SRC in most European countries (Larsson et al., 2003; Dimitriou, 2005). In this case, P concentration in this water would be c. 3 mg P/l, that is 7 times the average P concentration in the treated wastewater in Sweden (SCB, 2010), and ca. 22 kg P/ha would be applied with wastewater. This would however require much larger areas, i.e. 160 000 ha irrigated with wastewater, and approximately equal areas would be applied with sludge if all P would be applied to SRC.

Despite the calculations above, it is almost certainly not feasible for all P contained in wastewater and sewage sludge to be applied to SRC fields, since there are both technical and non-technical constraints that would permit only part of this P to be applied to SRC (Biopros 2009). However, even if only 10% of all P entering the wastewater treatment plants in Sweden were applied to SRC fields, *c.* 50 000 ha could be cultivated with SRC and this would imply four times more SRC than the current situation. In addition, and from a European perspective, if 10% of all P was recycled in SRC in EU27, then *c.* 600 PJ energy would be produced (*c.* 10% of all renewable energy produced in EU27). In this case, and even if such a limited proportion of P were recycled, SRC would become an established crop in Europe, which would enable an increased production of biomass for energy, and more cost- and land-efficient bioenergy systems. Consequently, there should be fewer conflicts with other land uses (*e.g.* food), and opportunities for local solutions for treatment and utilisation of nutrient resources which would otherwise be considered as waste, while simultaneously benefitting SRC farmers and producing biomass for energy.

Table 4. Theoretical estimations of land required if all available sewage sludge and wastewater would be applied to SRC, and consequent increases of the renewable energy amounts in different European IEA Bioenergy T43 countries (parts of this Table can be found in Dimitriou and Rosenqvist, 2011).

	Population (Millions)	SRC area to be fertilised with all available ss (1 000 ha)	SRC area to be fertilised with all available ww (1 000 ha)	Arable land surface with SRC fertilised with ss (%)	Arable land surface with SRC fertilised with ww (%)	Energy produced from SRC if all ss applied (PJ)	Energy produced from SRC if all ww applied (PJ)
EU-27	495.13	35673	1505	34	1.4	5636.3	309.2
Denmark	5.45	436	18	18	0.7	62	3.4
Finland	5.28	422	17	19	0.8	60.1	3.3
Germany	82.31	5931	250	50	2.1	937.0	51.4
Ireland	4.31	259	11	26	1.1	49.1	2.7
Italy	59.13	3550	146	50	2.1	673.1	36.9
Netherlands	16.36	1179	50	111	4.7	186.2	10.2
Sweden	9.11	505	23	19	0.9	103.7	5.7
UK	60.85	3654	150	60	2.5	692.7	38

CONCLUSIONS

The use of sewage sludge and wastewater to fertilise SRC offers both environmental advantages and economic profit to farmers growing SRC, through reduced fertilisation costs and increased biomass production. The economic profit of farmers can be substantially increased if this method is used instead of other wastewater treatment alternatives. Even if a small amount of the P entering the wastewater treatment plant were applied to SRC in the form of wastewater, sewage sludge or both, the agricultural land planted with SRC would increase markedly, leading to a considerable increase in renewable energy.

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IEA Bioenergy

IEA Bioenergy is an international collaboration set up in 1978 by the IEA to improve international co-operation and information exchange between national RD&D bioenergy programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use. Currently IEA Bioenergy has 22 Members and is operating on the basis of 13 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

IEA Bioenergy Task 43 – Biomass Feedstock for Energy Markets – seeks to promote sound bioenergy development that is driven by well-informed decisions in business, governments and elsewhere. This will be achieved by providing to relevant actors timely and topical analyses, syntheses and conclusions on all fields related to biomass feedstock, including biomass markets and the socioeconomic and environmental consequences of feedstock production. Task 43 currently (Jan 2011) has 14 participating countries: Australia, Canada, Denmark, European Commission - Joint Research Centre, Finland, Germany, Ireland, Italy, Netherlands, New Zealand, Norway, Sweden, UK, USA.

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