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BIOPROS

Solutions for the safe application of wastewater and sludge for high efficient biomass production in Short-Rotation-Plantations

Collective Research Project

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PREFACE

This report comprises the results from the work accomplished under task 1.4 of the Collective Research project BIOPROS “Solutions for the safe application of wastewater and sludge for high efficient biomass production in Short-Rotation-Plantations” which is co-financed by European Union’s the 6th Framework Programme. The report was elaborated under leadership of the Swedish University of Agricultural Sciences (SLU) with assistance from the following partners:

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1 EXECUTIVE SUMMARY

The treatment and reuse of wastewaters or municipal sludge to Short-Rotation-Plantations (SRPs), mainly grown for energy purposes, is a rather new approach aiming at utilising the nutrients in several waste residues which further contribute to enhanced biomass SRP growth. Therefore, the research related to this subject refers to both the cultivation of SRPs and the application of the different waste residues, and its consequences.

Research for the implementation of intensively cultivated SRPs aiming at highest biomass production was initiated already in the 1970s and involved mainly research on broadleaved trees with the following characteristics; fast-growing, cultivated in dense stands, harvested after short periods, and have good coppice ability. Based on that, mainly willows, poplars and eucalyptus have been used for establishing SRPs, and a series of research projects have been initiated investigating aspects as the suitability of tree species under certain climatic conditions, crop management including choice of land, crop establishment, fertilisation, weeding and pest management, harvest intensity etc., and environmental and economic issues. The intensive cultivation character of SRPs, which requires a frequent nutrient input for highest production, and the fact that SRPs are non-food, non-fodder crops, have lately led to the idea of applying wastewater/sludge to SRPs with relative low hygienic risks. Research related to such applications are mostly investigating environmental aspects as leaching of hazardous elements to the groundwater, accumulation of elements in the soil, air-pollution, aspects on the hygienic impact and on application technologies, combined with the SRP biomass produced, having therefore an integrated approach.

In most current research projects for wastewater/sludge applications to SRPs, the sustainability of the systems in terms of environment, health and management issues is under investigation. Although a lot of findings so far have contributed to a better understanding of best management practices and of the environmental and hygienic hazards involved, the “case-specificity” and the broad number of factors interfering for a successful application of the different waste residues, require either continuous monitoring “in situ” and/or risk minimisation approaches. Therefore, in every case, the amount of e.g. nitrates and phosphates leached to the groundwater, the amount of salts, N and P and heavy metals accumulated in the soil and taken up in the plant parts, should be continuously monitored for minimal hazards to sustainability and highest biomass produced. If larger agricultural areas with SRPs applied with wastewater/sludge are to be implemented in the future, then in turn future research should focus on evaluating the performance of different SRP species, grown on different soil types and applied with different kinds of residues in varying quantities, to cover a vaster range of such practices, and to establish empirical models useful for practitioners and decision makers.

2 INTRODUCTION

This report deals with the current situation in the field of Short-Rotation Plantations (SRPs), especially designed for treatment and reuse of wastewater and municipal sludge. The report contains three main parts; first an overview of the state-of-the-art in the field of SRP for wastewater treatment. Following this, an overview of ongoing research and development projects is presented. Finally, an analysis of gaps in knowledge is presented.

Within the BIOPROS project a definition of SRP has been adopted which implies that also non-woody crops such as perennial grasses (e.g. *Arundo donax*, *Phalaris* and *Miscanthus*) could be regarded as SRPs. However, the work within the project has a very strong focus on woody crops (e.g. *Salix*, *Populus* and *Eucalyptus*), and therefore this report deals only with woody SRPs.

Very large research efforts and investments have been put into the development of SRPs for pulp and timber. Substantial parts of these efforts are applicable also for SRPs used for wastewater treatment, but the main emphasis of the work in this report has been on R&D dealing with the combination of SRP and wastewater.

3 STATE OF THE ART OF SRPs, ESPECIALLY FOR WASTEWATER TREATMENT

The practice of growing trees or herbaceous crops on rotations shorter than 10-12 years in high density plantations to produce lignocellulosic feedstock for the pulp, board and/or energy industries is acknowledged in the literature by a variety of names, to separate such practices from the traditional forestry with a stand development of many decades until the final harvest. Some of these names include the more general “short-rotation plantation” (SRP), as well as “short-rotation forestry”, “energy forestry” (mostly in Sweden), “short-rotation intensive culture” (mostly in North America), and “short-rotation coppice” (mostly in the UK) (Mitchell *et al.*, 1999). The name SRP is used for implying a more general meaning, referred to every crop –tree or herbaceous- that is cultivated for the above-mentioned purposes.

The cultivation of SRPs has a long tradition and, at least in Europe, traces back to the Middle Ages (Burschel and Huss, 1987), when especially willow coppice has been widespread for different implementations, as e.g. the production of baskets. In Germany, mainly poplars have been used for paper production during the last centuries. In the US, sycamore was grown for paper- and pulp industry (Steinbeck, 1981). During the 1970s, following the oil crises, the emphasis of growing SRPs was stressed to the production of woody biomass for energy using fast-growing broadleaved trees, such as poplars, willows, alders etc., as an alternative to fossil fuels. These plantations were not conducted following the “traditional” forestry way, but were densely grown (up to 20 000 plants/ha in marginal and/or agricultural land) and under intensive management systems (field preparation, planting, crop management, harvest) (Christersson and Sennerby-Forsse, 1994; Mitchell *et al.*, 1999; Perttu, 1998).

During the following decades and up until today, some other plant species were also used in SRPs, such as eucalyptus, teak etc, depending on their geographic and climatic suitability. All the used SRP species, which are cultivated for biomass production in a specific area, have common characteristics; they are fast-growing under the local conditions, are cultivated in dense stands (to take maximum advantage of the available nutrients and light resulting in maximum growth), are harvested after short periods (usually between 2-8 years depending on the achieved biomass, but also annually in the case of herbaceous species or grasses), and have coppice ability (to reduce establishment costs). These cultivation methods are closer to agricultural practices than forestry due to their management intensity, which usually implies nutrient inputs in the form of fertilisation, and water irrigation, at least in warmer climates. Due to the maximum use of nutrients and the frequent harvests that deplete the soil from essential plant nutrients, the need for adding nutrients, especially such as N and P, is an important factor to achieve maximum biomass growth, which is the target in such SRPs. The additional cost of fertilisation of SRPs is high in all cases, particularly in developing countries (Heilman and Norby, 1998), but also in developed countries, contributing 20-30% to the costs (Hasselgren, 1998), and does not favour the cultivation of such plantations only for biomass production. Cheaper alternatives were therefore investigated to reduce those costs and to provide with multifunctional uses of short-rotation energy plantations. By using wastewaters that are usually rich in plant nutrients as nitrogen (N) and phosphorus (P), fertiliser costs would be zero, plant growth would be enhanced, and furthermore, waste products that would otherwise be treated at high cost were offered an alternative treatment, which also contributed to the sustainable society development with the previous-mentioned multi-advantages.

Therefore, the multifunctional use of SRPs for production of biomass and simultaneously for treatment and utilisation of wastewaters was proposed as a way of enhancing growth and

gaining other benefits for society. The use of wastewater for irrigation of crops is not a novel approach; advanced hydraulic systems for the collection and subsequent application of wastewater to farmland can be traced to the Mycenaean and Minoan civilisations in ancient Greece (Angelakis *et al.*, 2005). The transport and use of wastewater for irrigating agricultural crops was also recorded during the Middle Ages (Alker, 1999). In recent years, research programmes concerning the irrigation of large-scale tree plantations with wastewater were developed in Poland from the 1960s onwards (Kutera and Soroko, 1994). Efforts involving fertigation (irrigation + fertilisation) of tree seedlings with wastewater already in the 1970's were reported in the US (Brockway, 1982). In Sweden, where SRPs are mainly grown as short rotation willow coppice in dense stands for energy purposes already from the 1980's, to achieve a more cost-efficient cultivation for energy biomass that could be compared with e.g. energy from fossil fuels, it was necessary to reduce the input of conventional fertilisers. The use of nutrient-rich residues as an alternative, cost-efficient fertilisation method was proposed from the early stages of the development of short rotation willow coppice, and has been successfully practised (Perttu, 1992; Aronsson and Perttu, 2001; Hasselgren, 2003).

The waste products used for application on SRPs are covering a vast area of the available worldwide nutrient-rich waste products: municipal wastewater, wastewater from dairy industry, landfill leachate, diverted human urine (Larsson *et al.*, 2003), industrial wastewaters as log-yard runoff, meatworks wastewater (Guo and Sims, 2000) and other industrial effluents from e.g. textile factories (Bhati and Singh, 2003) or chicory industries etc, as wells as solid wastes as digested sludge (Hodson *et al.*, 1994) and granulated sludge (Labrecque *et al.*, 1997; Labrecque and Teodorescu, 2001) and wood-ash, have been used in SRPs as fertilisers. The most broadly used of the above-mentioned products are municipal wastewater (which contains nutrients that are closer to the nutrient needs of SRP plants (Perttu, 1994)), and sewage sludge, which contains high amounts of P and some N that can be cheaply applied on SRPs as a substitute to conventional fertilisers. Wastewater is usually applied on SRPs using drip irrigation system with trickle tubes covering the SRP fields, to avoid possible damage on the leaves (Aronsson *et al.*, 2002), and in other more rare cases with sprinkler irrigation systems. In north European climates, storage of municipal wastewater is required during winter, and therefore the total investment cost is increased. In the case of solid residues as sewage sludge, the application is conducted to newly harvested SRPs for practical reasons, and is following the legislative regulations existing for e.g. max. P and heavy metals loads. Application of different wastewaters should also follow regulations concerning the protection of surrounding environments, such as surface- and ground- waters, soil, atmosphere etc. Due to the fact that commercial large-scale SRPs dedicated for production of energy are established only in some parts of the world, the establishment of wastewater or sludge applications is currently occurring in a wider perspective only in north Europe (mostly in Sweden using willows), in Australia (using mostly eucalyptus) and in the USA and Canada (using mostly poplars and willows). Especially for sludge, the existence of large areas planted with SRPs is a prerequisite, if large sludge quantities would be applied. However, during the last years, efforts for establishing small-scale SRPs treating and utilising waste products produced from local wastewater treatment plants or industries have been reported elsewhere (e.g. Sweden, the UK, Poland etc).

The main benefit of the application of different waste residues on SRPs, as mentioned above, is the enhanced growth of the plants and consequently the increased biomass harvested. Due to the high effect of fertilisation on biomass production, wastewater application certainly influences the yield to a great extent (Sims and Riddell-Black, 1998). A lot of research has been carried out on the field of SRPs grown for biomass production in well managed stands, and a wide range of figures is available from literature. According to Mitchell (1995) and

Mitchell *et al.* (1999), and depending on location, climate, plant species, clones, etc., average biomass production is covering a wide range from 2.2-13.5 t dry matter per ha and year (DM/ha yr) for alder, poplar and willow. Heller *et al.* (2003) suggests average productions of 10 DM/ha yr. The achieved biomass production after wastewater application is asserted to be up to three times as high as without wastewater application (Hasselgren, 1998). In addition, Perttu and Kowalik (1997) as well as Labrecque *et al.*, (1997) stated 2-3 times higher yields in wastewater fertilised compared to unfertilised plots. In Canada, willow yields between 15 and 20 t DM/ha yr were already achieved (Labrecque and Teodorescu, 2001) in plantations fertilised with sewage sludge. Sims and Riddell-Black (1998) predict a feasible productivity with wastewater use and optimal handling of up to 20 t DM/ha yr for *Eucalyptus globulus*, which they affirm to be equivalent to an energy gain of 400 GJ. Guo *et al* (2002) found values of 24 t DM/ha yr for *Eucalyptus globulus* in New Zealand and claim up to 76% increase of productivity resulting from wastewater application.

The benefits of the society from the reuse of waste residues in a more economic and less energy-demanding way when adapting such unconventional ideas should not be underestimated. The treatment of wastewater on SRPs planted with willows in Sweden has been reported to reduce the cost for treating N substantially (Rosenqvist, 1997). The same can be mentioned for sludge application, for which the ban on deposits in landfills has increased the search for alternative treatment solutions. Finally, the economic benefits for the landowner/farmer should be also considered. However, this benefit is in direct connection with the effects of such applications on the environment, and requires limited or no negative environmental impacts in the soil, ground- and surface water etc, in terms of e.g. nutrient-in-excess and heavy metal input or accumulation. Therefore, extensive research has been conducted investigating such parameters, depending on the nature of the waste residue used on SRPs. In some cases, it has been reported that the ability of certain species used for SRPs contribute to reduce such problem (e.g Salix ability to take up certain heavy metals). For instance, Borjesson (1999a) claims that the estimated risk of accumulating salts, heavy metals and other components in the soil from wastewater irrigation is rather small. Kutera and Soroko (1994) provided data on chemical components in different kinds of soil, irrigated with wastewater for more than 100 years. They concluded that there was a limited impact on soil quality even after such long application times. The ability of heavy metal uptake in willow plantations even provides an effective soil remediation. If the applied wastewater itself has low contamination rates, the plants might still take up a large amount of contaminants from the soil. The general conclusion for SRPs is that the soil impact is low and more or less independent of applied wastewater rates (Larsson *et al.*, 2003). The leaching of organic and chemical compounds to the groundwater depends on the infiltration capacity, the soil texture, and the intensity of contamination. Over irrigation can, besides effects on plant performance and soil properties, cause N leaching to the groundwater (Al Jamal *et al.*, 2002). In this context, the conversion of ammonia to nitrate, which is less strongly adsorbed to the soil matrix, is a critical issue. Larsson *et al.* (2003) claim that high nutrient as well as metal concentrations in the groundwater are in some cases an effect of pre-existing high contents within the soil, which become mobilised after water application, instead of recently added components. If the selected site provides an appropriate soil type and the total wastewater amount is adapted to good operation practice, wastewater treatment will not specifically affect groundwater quality.

Investigations conducted during the last years demonstrate that after application to a Short-Rotation-Plantation, wastewater is purified also in hygienic terms and the number of most pathogenic organisms is reduced to a great extent (Larsson *et al.*, 2003). The achieved removal of pathogens depends on water pre-treatment, storage, and distribution techniques as

well as on humans' and larger animals' access to the area (Perttu, 1999). If the applied wastewater is pre-treated in a reasonable way, most of the pathogenic organisms will already be excluded at that stage. In the pre-treatment of wastewater applied in the investigation in Roma, Sweden. Larsson *et al.* (2003) found removal rates of above 99% for nearly all examined micro-organisms, resulting in values below the detection level in groundwater samples. In case wastewater is not sufficiently treated in advance, groundwater contaminations might appear, at least in case of coliforms. Consequently, there is some danger in distributing potentially highly contaminated water directly on the soil. As long as the sites are not well isolated, the risk of spreading diseases should not be ignored (Larsson *et al.*, 2003). Therefore, besides many different, state-specific regulations, the World Health Organisation (WHO) set standards for the use of wastewater in agricultural production (Hespanhol and Prost, 1994). But, as energy crops are not part of the human food-chain, the risk of spreading pathogens is by far not as high (Nielsen, 1994b; Sims and Riddell-Black, 1998). Applying wastewater on SRPs seems by all means to be less risky than direct discharge of wastewater to surface water recipients. It is in either case favourable to adapt the manner of distribution and to avoid spray or trickle irrigation to prevent potential problems for neighbouring humans as well as a greater impact on wildlife (Larsson *et al.*, 2003).

The existing experience on SRPs as means of wastewater treatment can be summarised as follows: The application of wastewaters on SRPs provides several advantages to the society in terms of enhanced renewable energy production and wastewater treated and reused. For a successful and environmental safe operation, careful site selection and proper management of the system is of crucial importance. The maximum applicable amount of wastewater is connected to the local climate conditions and higher loads of nutrients than the actual plant up-take could be applied, because microbial conversion and adsorption to the soil matrix contribute to nutrient elimination. If the above listed conditions are kept in mind, SRPs are as effective as wastewater treatment processes and no or only little impact on soil quality as well as on groundwater is expected. Hygienic risks seem to be limited in case of careful operations. A certain disadvantage is that a good treatment capacity is mainly available during the vegetation period of SRPs. The extra economic benefit generated by the biomass production largely contributes to public acceptance, especially at locations where cost considerations are obstructive to more technical solutions of wastewater treatment.

4 OVERVIEW OF CURRENT RESEARCH IN THE FIELD OF SRP AND WASTEWATER APPLICATION

In general, the available information related to European research activities on wastewater irrigation on SRPs is somewhat limited. The practice of applying wastewater/sludge on SRPs is a quite new approach in Europe and therefore not many research projects specially focused on such practices have been conducted in the past or are currently running. However, due to the increasing interest for such systems for treating and reusing waste residues and simultaneously producing biomass for energy, such research projects have been increasingly initiated during the last years. In most cases, research projects have been initiated in countries where the establishment of SRPs for production of energy biomass always had a strong tradition (e.g. Sweden, Denmark, UK etc), and in countries where the scarcity of water resources has lately led to alternative uses of wastewater, namely the reuse with wastewater in SRPs (research efforts in Spain, Italy, Greece etc). In other parts of the world besides Europe, irrigation of SRPs with wastewater or the application of sludge is not a common practice yet. Therefore, such research efforts will not be described in the following text. However, in cases where there are great similarities in the manner that the applications are conducted, some relevant examples from countries outside Europe will be mentioned.

Since the majority of the projects concerning SRPs did not include applications of wastewater/sludge, it was considered appropriate that projects related to SRP research aspects in general will be initially described. The SRPs irrigated with wastewater do not differ much from the “conventional” plantations where common practices for fertilisation and irrigation are used, and therefore the research conducted on several aspects for SRPs are very relevant to the BIOPROS approach. In the following an overview about the current research activities related to the suitable tree species used as SRPs will be given, followed by a similar description for the management of SRPs. The current research on the technologies for wastewater application and for the environmental and hygienic impact after such practices on SRPs will be described in following sessions. Finally, the current research on the economic aspects of such practices will be presented. For all the mentioned research topics, examples of current projects and results obtained for common SRPs and SRPs irrigated with wastewater will be given.

4.1 Suitable tree species

For European conditions there are few main tree genera that have been found more or less suitable for SRPs and that have been traditionally cultivated in plantations; such as *Salix*, *Populus*, *Eucalyptus* and *Robinia*. These species have been cultivated in Europe for different purposes since ages and in many cases are still used for traditional purposes, but also -at least in some cases- as crops for production of renewable energy. *Salix* trees (i.e. willow, osier or sallow) were grown in coppice (i.e. frequent and repeated harvest of resprouting shoots from stools) already by the Romans for use in basketry, fencing, and for supporting building constructions (e.g. Johnston, 1932). Nowadays, substantial European willow plantations are found in Romania, planted for wood production and environmental purposes (24,000 ha), and in Sweden (15,000 ha), planted mainly for energy purposes (Ball *et al.*, 2005). *Populus* (i.e. poplars or aspen) have been grown as single stem trees for centuries in Europe. Species from other parts of the world has been introduced in Europe leading, together with extensive breeding and hybridisation, to a situation where native European poplars are scarce, and this

has dramatically reduced the genetic base of European poplars. Presently, there are some 370,000 ha of planted poplars in Europe (Ball *et al.*, 2005). *Eucalyptus* was introduced in Europe already in the 18th century, and today, *Eucalyptus globulus* (which is by far the most common species used in European plantations) is one of the economically most important species on the Iberian peninsula planted on approximately 1,200,000 ha. It has become the main raw material supply of several pulp industries (especially in Portugal and Spain). *Eucalyptus* is a very controversial genus from an environmental point of view; several questions and concerns have been raised on its impact on a series of aspects as soil quality, biodiversity, forest fires etc. During the last decade several studies concerning the possibilities of managing eucalyptus as a coppice crop have been conducted. The results are indeed promising with good resprouting capacity, high growth rates, and high calorimetric energy yields (Dalianis *et al.*, 1994). *Robinia pseudoacacia* (common name “Black locust”) is another species that has been historically used in plantations for wood production in Europe. It originates from north-eastern USA but was introduced in Europe already in the 17th century (Keresztesi, 1988) and has become increasingly important in European forestry. *Robinia* is a N-fixing species enabling high growth rates without fertilisation even when grown on infertile soils. However, the ability to fix N makes *Robinia* less useful for many applications involving N rich municipal or industrial wastewater.

Some species of the above-mentioned genera have already been tested regarding their SRP suitability. Some of them have been found more suitable than others, mainly depending on the specific climatic conditions and on best local management practices. In the following part a general idea of the species’ suitability for wastewater irrigation or sludge application will be provided. Research conducted in UK and Sweden has mainly focussed on willows, and on the identification of most suitable varieties (i.e. clone) for different purposes (Dimitriou and Aronsson, 2005). One project that focused on the suitability of different willow clones was the “Genetic Improvement of Willow (*Salix*) as a Source of Bioenergy for the EC”, funded by EU, which was an effort to extend the Swedish breeding programme for *Salix* in the UK, Denmark, France and Germany, and addressed only willow cultivation without considering the use of the plantations for wastewater treatment. There is currently only one ongoing commercial willow breeding programme in Europe. The breeding was initiated by the Energy Forestry Project at SLU, Uppsala, Sweden, in the late 1970's and was then commercialised by Svalöf Weibull AB (SW Seed) in 1987 (Lindegaard *et al.*, 2001). The breeding program is now run by the Swedish company Agrobränsle AB aiming at introducing new varieties (clones) to the European market. Today, some 25 clones are registered with breeder's right by Agrobränsle of which 10 varieties are currently marketed (<http://www.agrobransle.se/salix/sorter>), and new varieties are being released annually. In UK, the IACR-Long Ashton at Bristol managed a willow breeding program funded by the European Willow Breeding Partnership owned by SW Seed, IACR-Long Ashton, and Murray Carter Ltd. This program lasted between 1996 and 2003 and resulted in 9 new varieties released on the market with breeder's right. Besides the commercial breeding efforts, many research projects on ecological traits and genetic aspects of willows are currently running. In Sweden there is a long-term project running at SLU, Uppsala, aiming at identifying and validating methods for making cheap and rapid assessments of willow clones in terms of water- and nutrient use efficiency (Weih and Nordh, 2002). The idea is to apply this approach in the earliest phase of testing progenies from crossings. The principle is also applicable for choosing the most suitable clones for specific phytoremediation actions. Another research project linked to the willow breeding at Agrobränsle is a national Swedish project aiming at studying frost hardiness, which can be of big importance in northern Europe if willows are to be irrigated with N rich wastewater since this might influence (delay) the onset of winter dormancy. At Cranfield University, UK research on water use efficiency of willows to

support future breeding efforts is being conducted (Luc Bonneau and co-workers). The water use efficiency can be of vital importance for choosing the appropriate clones for implementation of SRPs in dryer/warmer regions of Europe. Further, a breeding network on willow and poplars (BEGIN -Biomass for Energy Genetic Improvement Network, Dr. Angela Karp) is coordinated by Rothamsted Research, UK. The overall objective of this project is to provide a breeding programme and plant materials that will allow further improvement of the short rotation coppice willow crop, focussing on the generation of high yielding, pest and disease-resistant elite genotypes that are optimal for UK conditions.

For poplars, much less research compared to willows has been conducted, at least in terms of field tests related to coppicing and application of residues in general. This is also depicted in the research related to the introduction of suitable species or varieties for poplars. One such project aiming at developing both empirical and process-based growth models for poplars and willows in the UK is the project “Yield Models for the Energy Coppice of Poplar and Willow”, coordinated by the Forestry Commission Research Agency (Prof. Sam Evans and co-workers), co-funded by the Department of Trade and Industry (DTI), Forestry Commission and the Department of Agriculture and Rural Development in Northern Ireland (DARD-NI). The overall objective of the current phase of this long-running project (1996-2005) is to develop models which relate the yield obtained from energy coppice of poplar and willow to site factors and clonal characteristics. Another EU financed project for poplars that involves 10 different European partners, POPYOMICS, aims to use the latest techniques in molecular genetic mapping, genomics and the physical sequence of poplar, as available, to define gene that determine yield and disease resistance in *Populus* with the aim of improving this species for growth across Europe as a bioenergy and timber crop. The long-term ambition of POPYOMICS is to develop new genotypes of *Populus* with improved potential for fast growth, carbon sequestration below ground and optimised wood production for harvest. “Populus DB” is an open resource for poplar genomics aiming at the genome sequencing of *Populus* and the building of a database. UPSC (Department of Plant Physiology, Umeå University) and Department of Forest Genetics and Plant Physiology, SLU Umeå and Department of Biotechnology, KTH Stockholm are collaborating in this project, with financing contribution from Knut and Alice Wallenberg Foundation, Kempestiftelserna, the Foundation for Strategic Research, the Swedish Research Council and the Swedish Research Council for the Environment, Agricultural Sciences and Spatial Planning. Also in INRA France, research on poplar genomics is being conducted within the “PoplarDB” project, a poplar functional genomics database. The Poplar Genome Project is part of a larger INRA Genome Initiative, so-called LIGNOME, to construct genome databases for major forest species, and aims to create facilities of genomics resources for tree species. Within another UK-project, “BEGIN, Bioenergy Trees”, funded by the Department of Environment, Food and Rural Affairs (DEFRA), the development of poplar short rotation coppice has been promoted. The project is run by University of Southampton (Prof. Gill Taylor and co-workers). The principle objective of this work is to support the UK biomass industry by providing a supply of high yielding, genetically improved poplar material suitable for cultivation as short rotation coppice. The aim of the project is to provide the underpinning science for future developments in molecular poplar breeding and improvement.

The EU project EUROFACE (An integrated European scientific infrastructure for global change studies on forest and agroforest ecosystems utilising FACE (Free Air CO₂ Enrichment) technology) is chaired by Prof. Giuseppe Scarascia Mugnozza (Tuscia University-Viterbo-Italy). This project (2003-2006) includes 12 partners which belong to 7 European countries. It deals with an integrated research that will be conducted at the trans-European level on the role of forest plantations to mitigate greenhouse gases in support of the

Kyoto protocol and under conditions of climate change. The aim is to improve and make available to a larger scientific community a FACE infrastructure and to quantify uptake and soil storage of carbon as affected by global climate change and management. Therefore, the project will form a common research platform where several European and non-European teams will combine their expertises on a model ecosystem to falsify scientific hypotheses on the impact of climate change on forest ecosystems key processes. The FACE infrastructure is installed on short rotation plantations of various poplar species, that will be grown for a three-year period up to the rotation end, when final biomass production, wood quality and belowground allocation will be assessed. Furthermore, EUROFACE combines the FACE technology with the study of mechanistic, process-based responses. The use of the scientific results will be facilitated and widened for end-users through syntheses and integration archives.

The EU project VULCAN (Vulnerability assessment of shrubland ecosystems in Europe under climatic change) is chaired by Prof. Giuseppe Scarascia Mugnozza, (Tuscia University-Viterbo-Italy). This project (2001-2004) includes 6 partners which belong to six European countries. The climatic changes may have particular strong effects on vulnerable ecosystems such as shrublands, which are already subjected to other stresses such as elevated N deposition, intensive grazing or the risk of fire. VULCAN involves field scale manipulations of temperature and water at 6 European shrubland ecosystems (DK, UK, NL, HU, ES and IT) along a climatic gradient in order to:

- Conduct long term experimental manipulations of temperature and water at field scale. Temperature manipulations are conducted as night time warming by coverage of the ecosystem at night with a material reflecting the long wave radiation thereby heating the soils and plants. Drought manipulations are conducted by covering the vegetation during rain events by a transparent cover.
- Quantify the effect of increased air and soil temperature and extended drought on processes driving ecosystem functioning in European shrublands (plants, soils, fauna and soil water).

The project ESTABLISH (Molecular ecophysiology as tool for the selection of highly stress resistant poplar species for multipurpose forests) was focused at using the latest techniques in molecular genetic mapping, genomics and the physical sequence of poplar, as available, to define genes that controls the resistance to drought and salinity and to develop genetic markers suitable to molecular assisted selection.

4.2 Management

The management of SRPs has been under research investigations from the early beginning of the implementation of such plantations, due to the special features of such intensive tree cultivations that implies highest biomass production in short rotation periods. The research on the management of SRPs was related to a vast variety of cultivation aspects, as site selection and management, planting and plantation design, harvesting, pest control, fertilisation, irrigation and others. In a later stage and after some years when application of wastewater was starting to be considered as a way for fertilisation of the SRPs, research was conducted looking at aspects related with wastewater management as application techniques, amounts of wastewater/nutrients applied and others. However, since the aim of wastewater application in SRPs is the combined result of biomass production and wastewater treatment, the research on SRPs applied with wastewater has not been largely different from the research on management of “conventional” SRPs, at least when it comes to research on e.g. cultivation

management and pest control. Therefore, in the coming text, and especially in the first part, the focus will be on the current research on management of SRPs. Additional information related to the management of SRPs irrigated with wastewaters will be given in a separate part of the text, following the general description of the research on the management of SRPs.

The first extensive and large-scale efforts for producing biomass for energy by cultivating SRPs as an alternative to fossil fuels were conducted in Sweden after the oil crisis in the 1970s, with the intention of replacing fossil fuels by new energy sources. Extensive research to identify fast-growing species that could be grown intensively for use in energy production suggested that willows grown in coppice systems were the most suitable (Sirén *et al.*, 1987). The land that was initially thought to be used for those first efforts was previous forests and marginal land as peat bogs, which were not very productive and did not facilitate with high biomass growth. However, from the 1990s it was clear that there was and would be more agricultural soils available for production of SRPs (Sennerby Forsse and Johansson, 1989), and with the changes of the EU policies towards cultivation of food crops, the use of soils for agriculture was proposed for best practices of SRP cultivation. The choice of land for SRP cultivation is partly “case specific”, since it depends on the species used in SRPs. Willows (*Salix* sp.) have been proved to perform better in terms of growth and their commercial cultivation as SRPs dominates mostly in north and central Europe. Therefore, in this section we will refer mostly to short rotation willow coppice management, and will specify when we are referring to other species than willow.

4.2.1 Establishment

The choice of land for willow SRPs was investigated in the report “Short Rotation Willow Coppice - Growers Manual” (Danfors *et al.*, 1998), which was a Swedish effort. The Swedish version was funded by the Swedish Farmers' Foundation for Agricultural Research, Swedish National Board for Industrial and Technical Development and Vattenfall AB. The work of translation and adjusting in English was partly financed by the EC, DG XII within the FAIR Programme, in close association with project AIR2-CT94-1617 and partly by the ALTENER programme. In the report it is suggested that mineral soils (from sandy loams to heavy clays) should be preferred over organic soils due to weed control problems, and that areas susceptible to summer frost should be avoided for SRP cultivation. Comparisons between the preferable soils are also given. The DEFRA, UK, has developed a manual with the title “Growing Short Rotation Coppice” (DEFRA, 2002), where guidance for the choice of sites for SRPs in the UK is provided. Heavy clays are associated with slow establishment but with high productivity once established. A more detailed description for the site selection of SRPs with *Salix* and poplars in UK was given by Forestry Commission’s practice note written by Tubby and Armstrong (2002). It is suggested that besides the soil conditions, aspects as climate, landscape, archaeology and biodiversity should be considered for best site selection. The land preparation before cultivation and the sites selected are closely related to “things to consider” for the SRP site selection. For instance, soil compaction problems in ex-arable soils could be avoided by conducting subsoil ploughing in the preparation phase. Soil compaction issues for SRPs were investigated under the project “Effects of soil compaction on biomass production in short rotation coppice of willows” by the Institute of Water and Environment at Cranfield University, financed by DEFRA. It was suggested that if soil compaction problems are present, these should be alleviated within the cropping area but not in the zones to be wheeled. The loosening operations can be executed with the tractor operating in the future wheel zone. Unless very severe compaction exists which would impede grass development, the deeper loosening on the headlands should be avoided.

A lot of research related to the management of SRPs has been conducted concerning the establishment (plantation design, spacing, plant material, planting techniques etc) of such plantations especially in the UK and Sweden. Research on planting design of SRP depends on the selected species. For willows, projects as “Low-Cost Establishment Systems for Short Rotation Coppice” (Border Biofuels Limited (UK) and ADAS (UK), co-funded by Border Biofuels and the UK DTI through ETSU); “Initial spacing of poplars and willows grown as arable coppice”(driven by ETSU for the DTI, report written by Armstrong and Johns, 1997); “Crop physiological responses to plant density and harvest frequency in short rotation coppice” (conducted by ADAS Consulting, financed by DEFRA); “Can New Plantations of Salix and Miscanthus be Established with Reduced Manual Labour?” (Danish research); A Trial of Suitable Planting Machines for Project ARBRE (project was co-funded by the UK DTI and ARBRE Energy Ltd) have resulted in the adaptation of the existing planting densities and planting machinery used in the different countries where commercial practices of SRP cultivations take place. These practices obtained after the above-mentioned research are described in detail by Danfors *et al.*, (1998), Tubby and Armstrong (2002) and in DEFRA (2002). Scientific research concerning the planting density for SRPs is continuously conducted since the planting material of Salix that is being used in commercial plantations is constantly changing with new varieties being introduced. Agrobränsle AB, which is a leading company for conducting planting of Salix in Europe, suggests that around 13-14 000 plants per hectare should be planted for best SRP cultivation practices (www.agrobransle.se). Some years ago, the respective number for newly Salix plants established in a plantation was equal to 17 500. Concerning the plant material used for Salix cultivation, the research conducted and currently conducting has focused on species of *Salix schwerinii*, *S. viminalis*, *S. triandra*, *S. dasyclados*, and crossings between them (see also section 4.1 about the suitable species for SRPs). Some projects conducted at the initial phase of commercialisation were concentrated on the type of planting material, e.g. the “Benefits and drawbacks of long stems in willow plantations” (EBPS Foundation) looked into the differences between long stem plant material and cutting material of Salix. The current planting methods occurring in commercial plantations suggest that the results of the above-mentioned projects indicated that planting with Salix cuttings of about 20-25 cm is preferable. The planting machines that have been developed for such practices have been modified according to the material used for planting, e.g. Salix cuttings. The research conducted within the above-mentioned national and international projects, suggest that for commercial planting of willow the following planting machines are used: the Salix Maskiner “Step Planter”, which has been designed to make use of 2 or 3 m long willow rods which are cut into 20 cm lengths by the machine immediately before planting; the Autstof planting machine, which uses smaller cuttings of willow drilled into a shallow furrow, has returned the lowest unit cost but in a very dry year the shallow planting depth may result in mortality through desiccation. Research carried out in Northern Ireland by DARD-NI has shown that planting billets may result in poor growth during the establishment period; the lay flat system plants twin rows of 2 or 3 m long rods lying horizontally, end to end, just under the soil surface. Shoots and roots develop from the buried rod. Border Biofuels Ltd, together with Hvidsted Energy of Denmark, have developed this ‘lay flat’ planting system. During the planting season 2005, Agrobränsle AB tested a new developed planting machine in Sweden, which is supposed to reduce planting costs considerably. However, no data is yet available on its performance.

For poplars used for production of energy biomass, research on planting techniques has been conducted in Europe focusing mostly on the planting density, but not in such extend as for willows, probably due to the fact that poplar and eucalyptus cultivation for such purposes is not widely used. Nevertheless, experiments under the project “Effect of rotation age and

plantation density on the productivity of several poplar clones on short rotation in Spain” were conducted testing different planting densities of poplars, resulting in higher biomass produced from the densest stands. Similar results were obtained by experiments under the project “Initial spacing of poplars and willows grown as short rotation coppice”, conducted in the UK (funded by DTI, conducted by ETSU). Similar research was conducted in other central European countries testing poplar densities for maximum production (“The INRA Short Rotation Coppice programme”, France, and report from Friedrich (1999) for Germany. In general, the plantation densities suggested for poplar SRPs (around 10,000 plants per ha) are lower than those for willow SRPs and it can be commented that research on the appropriate density of poplar short-rotation plantation is not developed as much as for willows due to limited commercial importance, and the plantation density differs greatly depending on site characteristics (purpose of plantation, plant material, soil conditions etc). Within the EUROFACE consortium, the project POPFACE has as an objective, among others, to evaluate the amount of carbon being sequestered in the biomass and in the soil of intensive bio-energy forest plantation in relation to various management regimes (coppice vs. single stem, fertilisation, *Populus* species choice). For eucalyptus, research on management techniques in Europe is generally limited and much less than in countries as Australia, New Zealand, USA, South Africa and others. For specialised research on plantation techniques for eucalypts as SRPs the research is even less than that for poplars. Almost entirely the species *E. globulus* is used which is very frost sensitive and cannot be grown north of the Iberian peninsula. The planting densities for eucalyptus plantations vary in the different countries and it can be 1,800-3,500 saplings per hectare in France (Bewa, 1999; research within the ADEME project based on old research of AFOCEL) and up to 40,000 plants in Spain (Luger, 2003). The EU project “Improvement of Eucalypt Management – An Integrated approach: Breeding, Silviculture and Economics” (AIR3 – CT1678, AIR programme, participants from Spain, Portugal, France, Italy, UK, Greece), gives also information, among others, on the plant density of SRPs with eucalyptus (Pereira, 1998).

In Italy, the general objective is to identify the most promising species and to set-up fully mechanized production chains from planting in the field to delivery of the biomass at the industrial plant. Some experimental trials and about 200 hectares of demonstration fields with poplar, willow, *Eucalyptus* and black locust have been established to assess productivity and the effect of planting density and rotation length. The programme is divided into following research topics; species and clone selection, small-scale cultivation trials, mechanizations studies, storage studies, environmental studies.

Species and clone selection. The selected poplar, willow and eucalyptus species were subjected to clonal tests to establish their ability to be frequently coppiced and their productivity in terms of dry matter at high planting densities and short rotation time (one or two years).

Small-scale cultivation trials. Several small experimental field trials with poplar, willow and eucalyptus were established since 1993 at several locations in Italy (Sardinia, Piemonte and Tuscany), to assess productivity and cultivation techniques. Poplar and *Eucalyptus* seem the most productive plants for SRF energy use. Willow appeared extremely sensitive to dry conditions in the summer season and is therefore less suitable for the Mediterranean climate. The best mean annual yields per hectare were achieved by the poplar species *P. deltoides* (9.2 t/year dry matter for a density of 7100 trees/ha).

Environmental studies. Experimental plots for studying environmental issues regarding poplar cultivation for SRF were established in 1996 at the University of Pisa. Three crop types are compared; normal food crops (barley and sunflower), high-input poplar SRF (complete fertilisation, mechanical and chemical weed control), and low-input poplar SRF (minimum tillage, low fertilisation, only mechanical weed control). Also some research is done into

cultivation of herbaceous crops to reduce soil erosion. The findings will hopefully be used for setting environmentally friendly cultivation guidelines for SRF in Italy.

4.2.2 Weeding and pest control

Management practices concerning protection from weeds, pests and diseases gained a lot of attention from the early beginning of the establishment of SRP plantations. As mentioned above, most SRPs face problems during establishment due to the presence of weeds that hinder the growth of the newly planted SRP material during the first year. As a consequence, the biomass production of SRPs the next years is heavily reduced. This problem appears more frequent in agricultural clay soils under wet conditions, which is mostly the case for the areas in northern Europe where SRPs are commercially cultivated. Some examples from research projects related to weed control and conducted in the UK are the “Large scale trials of SRC for energy – Establishment, weed control and site hygiene” (conducted by ETSU and Aberdeen University, results included in several reports as Clay and Dixon, 1996; Clay, 1996; Willoughby and Clay, 1996); and “Integrated Pest Management for Short Rotation Coppice – Recommendations – Weeds” (carried out by the Game Conservancy Trust (GCT)). In general, a completely weed-free site is required at planting and must be maintained until the crop foliage shades out the weeds. Weed control can be divided into three phases; before planting, shortly after planting and after cut back or harvesting, and several herbicides depending on the country are used. Research on non-chemical weed control has also been conducted; “Non-chemical weed treatment in perennial energy crops”, but projects in Scotland, UK, indicated that the use of herbicides must be considered for a successful establishment of SRPs (project “An evaluation of herbicides for post-emergence use in Short Rotation Coppice” (2000), Biomass Energy Services Limited with Scottish Agricultural College (SAC)). A summary of this research can be found in Tubby and Armstrong (2002). Research on pest management for SRPs (mainly willow) varies between the different countries and is mainly depended on the intensity of the pest appearance in the different areas. In the UK and Sweden, leaf rust (*Melampsora* sp.) is the main concern probably due to climatic reasons. Therefore, a series of projects with the focus on UK and Swedish SRP willow plantations were conducted, and; (“Integrated, Non-fungicidal Control of *Melampsora* Rusts in Biomass Willow Plantations”, EU Project QLRT-1999-01585; “Integrated Pest Management for Short Rotation Coppice – Recommendations” (carried out by the GST); “Integrated control of fungal diseases in willow and poplars in bioenergy” (Lead Organisation: Rothamsted Research, financed by DEFRA); “Samspel mellan *Salix viminalis* och *Melampsora* i klonblandningar” (in Swedish, “Interactions between *Salix viminalis* and *Melampsora* in clone mixtures”, financed by STEM-P20030, conducted by SLU); and “*Melampsora*-rost på *Salix* i energiskog - variation och sporspridning” (in Swedish, “*Melampsora* rust in *Salix* energy forestry – variations and spore spreading”, financed by STEM- P12386, conducted by SLU). A general comment is that in most cases the use of costly chemical pesticides is avoided and during the last years, research on biological pest control have been conducted looking into a series of pests on SRPs, e.g. “Integrated crop protection in SRC willow production”, and “Pest population behaviour in relation to the biological chemistry of willows: towards optimisation of non-chemical control” (both conducted by Rothamsted Research but initiated at IACR-Long Ashton Research Station, Department of Agricultural Sciences, University of Bristol, Long Ashton, Bristol UK, funded by DEFRA); “The interaction between clones and beetles in clonal mixtures” (conducted by the DARD-NI); “Samspel mellan salixsorter, tillväxtbetingelser och angrepp av skadegörare” (in Swedish, “Interactions between *Salix* clones, growth patterns and pest attacks”, financed by STEM, P8415, conducted by Svalöf Weibull AB); “Resistens mot insekter i *Salix*-odlingar” (in Swedish, “Insect-resistance in *Salix*

plantations”, financed by STEM P12348, conducted by SLU); and “Växtskydd i intensivodlad lövskog mot svampar och bakterier”, (in Swedish, “Plant protection in intensive cultivation of broadleaved trees against fungi and bacteria”, financed by STEM, conducted by SLU). In many other cases, where insects are considered hazardous to SRPs, research has been focused on insect management; “Integrated Pest Management for Short Rotation Coppice – Insects” (carried out by the GCT); “Växtskydd i Salix-odlingar – Insekter”, (in Swedish, “Plant protection in Salix plantations”, conducted by SLU); and “Integrated crop protection in SRC willow production” (mentioned above). In some of the above-mentioned project reports, the problems to establish SRP due to game (rabbits, deer etc) are also addressed. Specific research on that aspect has been conducted under the project “Rabbit management for growers of short rotation willow coppice”, (conducted by CSL, financed by DEFRA and the DTI). Some other specific-oriented projects for SRP crop protection that can be mentioned are the “The giant willow aphid (*Tuberolachnus Saligus*) on SRC willow” (carried out by ICSTM, financed by DTI); “Populationsbiologin hos bladbaggar” (in Swedish, “Population biology of leaf hoppers”, financed by STEM, project P22165, conducted by SLU); “Bakterieangrepp i energiskog – koppling till frostsador (in Swedish, “Bacteria attacks in energy forests – association to frost damage”, financed by STEM-P12316, conducted by SLU); and the newly funded “Genetisk variation i inducerad resistens hos *Salix viminalis* mot gallmyggan *Dasineura marginemtorquens*” (in Swedish, “Genetic variations in induced resistance in *Salix viminalis* against the insect *Dasineura marginemtorquens*”, funded by FORMAS, conducted by SLU).

4.2.3 Operations

The majority of projects concerning SRPs are related to research on crop management activities, which include a variety of practices such as fertilisation, cutting cycle, harvest, storage, termination etc. The research on those aspects is related to best practices for SRP cultivation (usually Short Rotation Willow Coppice) aiming at the highest biomass production or quality. The projects mentioned below cover a broad range of the management aspects of SRP, and further information about the research subject, the institution that has conducted the research, and in most cases the funding organisation are given; “Large scale trials of SRC for energy – crop removal and restoration”, managed on behalf of ETSU for the DTI by Aberdeen University, examining different crop removal techniques (Grubbing out, Spray-off only, Spray-off and plough out, Spray-off and soil conditioning, Spray-off, establish fodder crop and plough out, Total soil mulching), and comparing differences in efficiency and cost; “Large scale trials of SRC for energy – Plantation productivity”, conducted and financed by the same organisations as the above project, covers yields achieved for different clones, yield sustainability, and growth models; “Termination of willow production”, conducted by SLU, Sweden, covers practical experiences from terminating short rotation willow plantations, separating the results in 3 categories (new plantations, 4-10 years plantations, old plantations), funded by Stiftelsen Lantbruksforskning; “Storage of Willow from Short Rotation Coppice”, conducted by the Danish Forest and Landscape Institute, research on moisture content, temperature in the piles, dry matter losses during storage and heating value of stored short rotation willow chips; “Harvesting of willow and poplar in Austria”, conducted by the Federal Institute of Agricultural Engineering BLT Wieselburg, Austria, research on agricultural, technical, environmental, energy and economic aspects in Austria; “Storage and Drying of Short Rotation Coppice”, conducted by First Renewables Ltd (with ADAS), funded by the UK Department of Trade and Industry, through ETSU, research on storage and drying of SRC as chips, sticks and billets; “Harvesting Systems for Short Rotation Forestry”, conducted by Technischen Universität München, research on the evaluation and the key characteristics and

field performance data of three harvest machines in Germany; “Mechanised Harvesting and Comminution of Short Rotation Coppice”, carried out by the Technical Development Branch of the Forestry Commission, funded by the UK DTI, through ETSU, and the UK Forestry Commission, research on outputs and costs and best harvesting methods from the most up to date UK research into SRC harvesting; “Harvesting machinery for short rotation coppice willow, Denmark”, conducted by Danish Forest and Landscape Institute, research on the same subject as the previous-mentioned project in Denmark; “Drying Short Rotation Coppice Wood Fuel”, carried out by Long Ashton Research Institute, in collaboration with ADAS and Banks Agriculture, funded by the UK DTI and managed by ETSU, research on arrangement and operation of a practical, on-site, fuel storage drying system; “Development of Harvesting and Storage Technologies Essential for the Establishment of Short Rotation Forestry as an Economic Source of Fuel in Europe”, funded by EU AIR3-CT94-1102, includes a series of smaller projects mentioned in this section; “Bördighetsuppbyggnad i differentierat gödslade Salixbestånd (in Swedish)”, carried out by SLU, Sweden, funded by STEM, fertilisation effects on SRP willow plantations fertilised under different regimes; “Utveckling av befintliga basmaskiner för Salixskörd (in Swedish)”, carried out by Agrobränsle, funded by STEM, development of existing harvest machines for Salix SRPs; “Yield models for energy coppice of poplar and willow – phase IV”, carried out by Forestry Commission Research Agency, UK, funded by DEFRA, DTI, Forestry Commission and DARD-NI, the aim is to develop models which relate the yield obtained from energy coppice of poplar and willow to site factors and clonal characteristics; Fertilisation of SRC willow, conducted by DARD-NI; “Willow coppice agronomy in Wales”, carried out by Cardiff University, funded by the local Government; “A study of SRC productivity in the second rotation at the ‘Farm Wood Fuel and Energy Project’ sites”, carried out by Writtle College, funded by DEFRA and DTI; “Crop physiological responses to plant density and harvest frequency in short rotation coppice”, conducted by ADAS Consulting Ltd, funded by DEFRA; “Energy coppice: site/variety/yield interactions”, carried out by Forest Research Station, funded by DEFRA; “Produktion och beståndsdynamik av energiskogsodling under senare omdrev (in Swedish)”, carried out by SLU, financed by STEM, research on production and site dynamics of willow SRP under cultivation after many cutting cycles; “Ekologisk karaktärisering av salixkloner med hänsyn till vatten- och näringstillgång (in Swedish)”, carried out by SLU, financed by STEM, research on growth and nutrient efficiency differences between clones.

Additional to the above-mentioned projects focused on willow SRPs, there is a number of projects that focus on other SRP species in Europe, such as poplars, eucalyptus etc. Some of this research has been conducted under the projects named below: “Effect of rotation age and plantation density on the productivity of several poplar clones on short rotation in Spain”, carried out by CIEMAT at CIEMAT’s Center of Renewable Energies Development located in Soria, plant behaviour at different plantation densities and different treatment regimes (fertilisation, irrigation) were tested; “Monitoring the second rotation of short-rotation cultivation of poplar”, conducted by ADEME Agriculture & Bioenergy Department, France, research on determination of production conditions required to obtain at least 10 tonnes of dry material per hectare and per year for the second rotation of SRC (short rotation cultivation) of poplar, maintaining the same harvesting conditions as at the end of the first rotation; “Poplars – a multiple use crop for surplus arable land” (PAMUCEAF), involved a series of European institutions, funded by EU (FAIR-CT98-4193), aim to produce revised recommendations for poplar production on arable or mixed farms - ensuring maximum profitability, full integration with other farm enterprises and environmental acceptability (Continuation of IR2-CT92-1753: Poplars for Farmers); “Cut and comminute harvesters for short-rotation poplar”, carried out by TU Munich, parallel research with the respective project for willow (see above); “Development of a prototype harvester for poplar and eucalyptus under Italian condition”,

performed by the Research Institute for Agricultural Mechanisation (ISMA), research on the application of Northern European harvesters under Italian conditions which showed that adaptation should be made for appropriate use under Italian conditions; “Research support for developing short rotation coppice (SRC) poplar”, conducted by Southampton University, funded by DEFRA, with focus on production and development of short rotation poplars in UK; “High density coppice culture of poplar”, carried out by University of Antwerp, funded by Fund for Scientific Research Flanders, research on clone differences in biomass production, shoot and stool mortality of poplar short rotation plantations; “Definition of criteria and indicators for the sustainable management of European eucalyptus stands”, carried out by a number of partners from France, Portugal and Spain, funded by EU (FAIR-CT97-3856); and finally the above mentioned EU project “Improvement of Eucalypt Management – An Integrated approach: Breeding, Silviculture and Economics” (AIR3 – CT1678).

The Italian poplar project includes operational studies:

Mechanization studies. Nursery operations, planting and harvesting are considered for mechanization. Both prototype machinery from Northern Europe and from Italian manufacturers were tested and necessarily adapted. Harvesting appeared the most critical phase for SRF. The four machines tested were all able to harvest under Italian conditions. However the wet, soft soil condition in Italian winter did cause some problems of soil damage for the Scandinavian prototypes, especially due to the heavy carts loaded with chips and towed by tractors.

Biomass storage studies. During the first tests in 1995/96, whole trees and chips from SRF plantations (2-year old poplar) were stored in piles in the open air under periodic monitoring. One pile was stored uncovered (130 tonnes), 4 piles were stored both covered and uncovered with and without passive ventilation. For chip storage it was found that the rainwater penetrates deeply into the piles, thereby activating the fermentation process and causing temperature increase. Any protection from plastic films placed on top did not offer particular advantages. During storage, the average moisture contents did not change. For whole trees, the moisture content decreased during the first 4 months from 61% to 20%, eventually reaching 15% after a year. The measured loss of dry matter in a year varied for chips from 12% (with ventilation) to 23% and for whole trees 22%.

4.2.4 Management of SRPs irrigated with wastewater

The use of SRPs for irrigation with wastewater to achieve higher biomass production and simultaneously to treat the wastewater has been lately under extensive research. A number of projects have been investigating all aspects related to such practices, management, biomass produced, environmental problems implied after such applications, and others. The projects referred and described below are covering the parts of research that are specifically related to wastewater applications on SRPs, and their specific implications, and therefore should be seen as a complement to the already above-mentioned projects that are related to SRP management research. Furthermore, the below-mentioned projects of this section will not include projects related to the wastewater application techniques or to projects specifically related to environmental and hygienic aspects, since such research projects will be commented in detail in other chapters. However, in many cases, due to the integrated approach of such practices, one project is referred to a range or research aspects, and therefore some projects related to wastewater application on SRPs will be repeatedly mentioned while covering different research aspects.

Under the EU funded project “Biomass short rotation willow coppice fertilized with nutrient from municipal wastewater” (BWCW) (FAIR-CT97-3947) experimental SRP fields were established in four European countries from both the south and the north (UK, Sweden, Greece, France). The SRP fields were located in the vicinity of a municipal wastewater treatment plants and wastewater was applied to the fields. The objectives of this project were to study the growth and biomass productivity of SRPs under the above-mentioned conditions, to determine the most suitable irrigation rates of wastewater for environmentally safe wastewater applications, and simultaneously maximising biomass production, to monitor leaching of minerals to deeper soil layers and to assess which irrigation rates are suitable for minimised groundwater pollution, to assess the uptake of certain minerals into the various plant components as well as their retention in the various soil layers, to investigate the effect of the SRPs/wastewater irrigation system on landscape, sanitary implications, pests and diseases and to evaluate the economy of the system in terms of purification of wastewater and production of biomass on farmland. Concerning the crop management aspects of this experiment, the plant material used in all these the experiments was the same (the Swedish clone Jorr), the irrigation schedule was different for each site depending on the local conditions and adapted to the potential evapotranspiration of each site, and the types of wastewater varied significantly due to their different sources. From the results, it is reported that the biomass produced varied from area to area, and the responses to the different irrigation levels concerning the biomass produced were different. In some cases, the reported biomass production varied and could be three times higher in plots supplied with wastewater compared to the control, but in other cases differences between the different wastewater application levels were not observed. The establishment of the crop, and therefore the weed control was of utmost importance for the successfulness of the best biomass produced, and differences in the effort for weed control were observed for each place. The assessment for rust (*Melampsora*) infection indicated that in Greece and Sweden no rust was evident, and that rust scores were higher at the French trial than that in Northern Ireland, but with variation from year to year. For both these sites, although there were some indications that rust infection was greater in the higher wastewater irrigation treatments, when the results were statistically analysed there were no significant differences between treatments. Leaf damages were more severe in all the aspects studied with the progress of years, except galled leaf margins in France. Damage by chrysomelid beetles was very severe in France as were abiotic stress symptoms in Greece. Control trees were less stressed concerning the leaf beetles than those receiving wastewater treatments. Also mite frequency was lowest in the control treatment. Stem die-back did not show any pattern related either to irrigation treatment or any obvious environmental variables and was probably due to frost damage followed by secondary *Fusarium* infection of the weakened stems. Under another related project, “Utnyttjande och behandling av restprodukter i Salixodling” (in Swedish, “Use and treatment of rest products in Salix plantations), funded by STEM (Project nr P 12267–1), the work conducted by SWECO VIAK AB, Sweden, resulted in a comprehensive manual for guidelines concerning the wastewater and sludge application on SRPs was produced by SWECO-VIAK (Hasselgren and Lundström, 2003a). In this report, guidelines and advice for a range of SRP cultivation aspects -irrigated with wastewater- as planting, weed and pest control, harvest and soil condition, in relation to irrigation and hydraulic loads are discussed, gained from experience obtained by different experiments with wastewater on SRPs with willow, conducted in Sweden. A similar manual was produced for irrigation of SRPs of willow with landfill leachate (Hasselgren and Lundström, 2003b). Within another Swedish project, “Rening av rejektivatten i vegetations-filter av Salix”, (in Swedish, “Cleaning of supernatant in vegetation filters with Salix”), financed by STEM (project P12298-1, conducted by SLU and Enköping municipality), research on the sustainability of the system related to environmental issues and application rates of wastewater has been conducted. This

project is continued with the project “Reningsseffekt – miljöpåverkan hos Salix för avloppsrening”, (in Swedish, Cleaning effect – environmental effects on Salix for cleaning of waste products, financed by STEM (STEM-projekt P13038), conducted by SLU), in which the environmental effects and the biomass produced under a large-scale systems where a 76 ha Salix SRPs irrigated wastewater are investigated. Preliminary results indicate, that biomass production, although site-specific, is enhanced on the areas irrigated with wastewater.

Projects related to the management of SRPs irrigated with wastewater, in other countries than Sweden, have also been conducted or are still running. In the UK, the project “Bioenergy crops and bioremediation - a review” (financed by DEFRA, NF0417, funded organisation ADAS Consulting Ltd), investigated –among others- the effect of wastewater and sludge applications within the legal limits, on the biomass production of willow SRPs. It was found that the good growth of SRPs is a prerequisite for the effective treatment with limited environmental hazards of the waste residues (see more in chapters below). A similar project examining the suitability of SRPs for treatment of wastewater in Belgium has the title “Tertiary waste water treatment using short rotation willow coppice in Belgium” (funded by the Walloon Region, conducted by the University of Louvain). Two different willow clones grown on 1-ha plantation were compared for their ability to treat and utilise the tertiary treated wastewater. The preliminary results have shown no changes in the biomass produced from the different treatments, but the amount of N applied in SRPs showed no hazardous environmental effects. There are also other national implementation research projects carried out on small municipalities with SRPs applied with wastewater. Such are the LIFE Environment project “Sustainable wastewater purification in Estonian small municipalities”, (carried out with the help of Estonian Agricultural University), with the objective to build different prototypes of wastewater purification systems in two rural municipalities of Estonia and to present the innovative sustainable wastewater purification systems as one solution for local environmental/energy supply problems in Estonia. Another similar LIFE Environment project was initiated with focus in Bretagne, France, with the title WILWATER. The implementation of 100 ha willow SRPs treated with municipal wastewater from rural areas in Bretagne has been planned. The project “Water-Renew: Wastewater Tertiary Treatment Using Renewable Energy Crops” is also an EU LIFE Environment funded portfolio collaborative research project carried out by WRc Group in partnership with Queen’s University Belfast and Cranfield University. The project aims to bring this technology close to commercial scale implementation within the UK and provide another alternative to traditional tertiary wastewater treatment and a renewable energy source for future generations. All the above mentioned LIFE Environment projects looked only partly on management aspects; SRPs are cultivated as willow short-rotation coppice following the commercial way of cultivation already used in the north-European countries, and the established experiments monitor the amounts of wastewater that should be irrigated for environmental sound applications, the achieved biomass growth after the irrigation with wastewater, and other aspects like leaching to the groundwater, losses to the atmosphere etc (look below for more details about these aspects). A project that investigates in closer details the monitoring of wastewater application on SRPs is the WACOSYS “Monitoring and Control System for Wastewater irrigated Energy Plantations”, which is an EU funded CRAFT project involving partners from a range of European countries (Germany, Spain, Portugal, Finland, Poland, Estonia). TTZ (Technologie-Transfer-Zentrum Bremerhaven), EAU (Estonian Agricultural University) and WAU (Warsaw Agricultural University) are the RTDs involved in this project, which partly aims to develop, test and optimise the irrigation and fertilisation of willow and poplar SRPs with wastewater in an environmental and economic sound way, covering a wide range of European locations differing in climatic conditions.

Concerning other types of waste residues applied on SRPs in Europe, the application of landfill leachate is one of the most common ones. Research projects concerning the management of applications with this special kind of wastewater have been conducted in different countries. For instance, the project “Landfill Leachate Using SRC”, funded by RMC Environment Fund and conducted by WRc Waste Research Ltd, UK, the project “Bevatning av Salix med lakvatten från Ragnsells avfallsanläggning Högbytorp, Upplands Bro kommun” (in Swedish, Irrigation of Salix with landfill leachate from the disposal site of RagnSells in Högbytorp, municipality of Upplands Bro”, (financed by RagnSells AB and conducted by SLU and Lunds University), the project “Effect of soil compaction on productivity of coppiced willow Biomass production on landfill sites - investigating the feasibility of using landfill leachate for irrigation of short-rotation coppiced willows” managed by Cranfield University, some experimental work in Poland (Agopsowicz and Bialowiec, 2003) and the manual for landfill leachate developed by Hasselgren and Lundström (financed by STEM) give an overview of the existing experience of landfill leachate applications on SRPs (mostly willow). A series of experiments have been also conducted having in focus sewage sludge applications on SRPs; the project “Application of sludge and wood ash mixtures to Salix on agricultural soils: Effects on biomass production, fuel quality and nutrient- and heavy metal status in the soil”, (financed by STEM and conducted by SLU), and other projects of local character in different European areas, examining the potential of sludge application on SRPs (Pulford *et al.*, 2002; Riddell-Black, 1998; Tsakou *et al.*, 2003), have been focused on the effect of sludge application on SRPs growth and on environmental aspects as the metal accumulation in soil and plants.

To conclude with the management aspects of SRPs irrigated with wastewater or applied with sludge, it must be commented that it is difficult to separate and to describe these aspects separately from the management aspects of SRPs in general. These have been (and are) studied in detail during the last years, and the knowledge acquired via the numerous projects conducted, can be applied to the concept of wastewater application on SRPs. However, specialised experiments concerning wastewater applications on SRPs are also being conducted in increasing numbers during the last years, investigating a range of different research aspects related to such practices. In most cases though, these aspects are not solely related with crop management aspects, but mostly to environmental implications, in conjunction with the biomass production achieved. Therefore, the collection above of research efforts for SRPs irrigated with wastewater should not be read isolated, but should be considered as one of the many research parts of this integrated approach and therefore should be read in conjunction with the following sections.

4.3 Technologies for wastewater application

It can be generally commented that the research activities -and the results provided- related to the technologies for wastewater application on SRPs are not usually accessible to the wider public since in most cases such research and development practices are conducted within private organisations, which have also commercial interests, and in general do not release their results or do not cooperate within bigger consortiums due to their economic interests. In addition, the irrigation techniques of SRPs with wastewater do not differ from the techniques used for irrigation of wastewater in agricultural crops, and which are regulated and affected mostly by the hygienic implications of such practices. As a result, a limited amount of information concerning current research can be described in this section. Therefore, in this session we will additionally try to shortly describe the existing wastewater irrigation methods with focus on the more used methods for SRP wastewater irrigation techniques, and describe

advantages and disadvantages of some of the methods in relation to the environmental and hygienic impact due to the adapted irrigation manner. In the last part of this session, sludge application techniques on SRPs will be described.

There are different techniques available for spreading of wastewater in SRPs. Concerning wastewater irrigation, the different methods can be in general separated in five categories, depending on the manner of wetting the soil: flood-, furrow-, sprinkler-, sub- and localised irrigation. The choice of which of the above-mentioned irrigation method would be used is governed in general by factors as the choice of crop, the wetting of foliage and aerial parts, the distribution of water, salts and contaminants in the soil, the easiness with which high soil water potential could be maintained, the efficiency of application, and the potential to contaminate farm workers and the environment. The implications for the hygienic risks will be analysed more in depth in the following chapter. In an evaluation of the above-mentioned methods conducted for FAO (Pescod, 1992), localised irrigation (e.g. drip irrigation) is considered to offer the most advantages for irrigation of all kinds of crops with wastewater, combining less salinity risks and best hygienic performance, despite the higher cost than the other costs. This conclusion is enhanced for SRPs, since a drip irrigation system will not cause problems while mechanical practices, as e.g. harvest, occur. Automatic drip irrigation systems controlled by timers, to involve as less labour involvement as possible and adjust irrigation to climatic conditions, are used in most cases when commercial applications of wastewater on SRPs take place in Europe (Hasselgren, 2003a). Root clogging is often a problem occurring, but the latest technological developments suggest advanced techniques against it (as e.g. the occurrence of herbicides in the inner surface of the pipes that prohibit root development). Research has also been conducted for estimation of the effects of unevenly distributed wastewater with drip irrigation on SRP willow growth (Aronsson *et al.*, 2002). It was reported that individual stool growth is affected by the distance to the nearest emitter of wastewater, but this effect would not be increased over time. Limited research specialised on sludge applications on SRPs has been conducted. Sludge applications on SRPs are taking place in newly planted or newly harvested plantations to avoid plant damage. The techniques for sludge applications on SRPs are in direct relation to the legislation of each country, and in all cases existing machinery is used to avoid additional costs. In most cases in Europe, the sludge applied on SRPs has rather low water content (solid) and has remained stored for a year to minimise odour and hygienic problems and is applied with common spreaders. In other cases however, and especially in countries outside Europe, sludge with high water content (wet) is injected some centimetres under ground to diminish odour problems and for better utilisation of the nutrients by the plant roots. One of the most promising approaches to apply sludge has been developed by the NI company Rural Generation Ltd. This approach includes sludge injection. A trailer tips the sludge directly into a bin auger which then takes the sludge to the sludge injector trailer behind a tractor through the field where it cuts a track in the ground, between the newly harvested/planted willow. A screw augers the sludge into the trench and discs on the trailer fold the soil over the sludge, completely covering sludge under ground. No research data is yet available for this system, though.

4.4 Environmental and hygienic impact

The environmental and hygienic effects of the irrigation of SRPs with wastewater or after application of sludge have been under extensive research, due to the fact that the acceptability of the public for such practices depends largely on their environmental and hygienic soundness. Almost all the above-mentioned projects concerning wastewater irrigation on SRPs include in their aims and hypotheses aspects related to the environmental consequences

and to the sustainability after such practices. Simultaneously, the cultivation of SRPs offers in general also a series of environmental benefits to the society, and so does the use and recycling of the wastewater treated and utilised for production of SRPs for energy biomass, instead of other costly conventional treatment methods. In the following text, a description of the current research activities on the environmental and hygienic impact being conducted in different European institutions and by different research groups is given. The scientific research groups involved in the research projects, the several projects themselves and some more information about the current research topics and activities concerning the environmental and hygienic impact of application of wastewater/sludge on SRPs will be described.

The cultivation of SRPs is generally very beneficial for the environment compared to conventional agricultural crops; nitrate leaching from a SRP is in general substantially lower than from conventional agricultural crops (Aronsson *et al.*, 2000; Mortensen *et al.*, 1998) and so are soil erosion losses. SRP cultivation may improve soil organic content and the biodiversity (Alriksson, 1997). However, applying wastewater or sewage sludge to SRPs may pose some threats for the environment in terms of groundwater pollution (nitrate, P, organic compounds, and pathogens) and soil pollution (heavy metals and persistent organic compounds, pharmaceuticals etc.). Such practices may also result in the release of trace gases to the atmosphere. In this context, release of ammonia (NH₃), methane (CH₄), and dinitrogen oxide (N₂O) are the gases of concern related to eutrophication and the greenhouse effect. Research on N treatment efficiency and leaching from SRPs fertilised with wastewater and/or sewage sludge has mainly been conducted in UK, Sweden, and Denmark. In UK, studies concerning nitrate leaching from SRPs with willow (without wastewater irrigation) have been conducted within the project "Nitrate leaching from short rotation coppice following establishment, harvest and crop removal", funded by DEFRA, conducted by ADAS Consulting Ltd, aiming to develop future N recommendations that can be adjusted to more effectively match crop needs. This project ran parallel to another DEFRA financed project related to the environmental effects of using SRPs for bioremediation. The project "Bioenergy crops and bioremediation - a review", conducted by ADAS Consulting Ltd, provided among others with research results related to the magnitude of nutrient and metal bioremediation where energy crops are grown, and with an evaluation of the magnitude of atmospheric emissions of CH₄, N₂O and CO₂ from different wastes applied to energy crops. It was concluded that despite the obvious advantages after such practices, special attention must be paid to the P amounts leached after repeated applications on SRPs and to the metal accumulation in the soil especially after applications of organic wastes as slurry and sludge, and that more research is needed concerning the gas fluxes in the atmosphere. Several studies on leaching from SRPs irrigated with wastewater have been conducted by WRc plc (Water Research centre, e.g. Alker, 1999 and Riddell-Black, 1998). WRc is presently running a EU-LIFE project "Water Renew: Wastewater Polishing using Renewable Energy Crops" in partnership with Queen's University Belfast and Cranfield University aiming at investigating the efficiency, financial and environmental benefits of using renewable energy crops to provide tertiary treatment of wastewater (project director Dr Miles Davis, detailed description of the project see above). Within another recent EU-funded project ("PAMUCEAF: Poplars - A multiple-use crop for European arable farmers", coordinator Christopher Britt, ADAS Ltd, UK) the potential environmental impacts of SRP poplar was evaluated. It was found that nitrate losses by leaching were low compared to values for arable land. However, the drainage from the SRP sites was so low that firm conclusions could not be drawn from this. Closely related to this research is the work conducted within the project "Biomass Production on Landfill Sites" at Cranfield University, aiming at determining the feasibility of treating and using landfill leachate as a source of water and nutrients for biomass production (coordinator

Dr William Stephens). Similar research topics are being studied at the University of Cardiff, Wales, UK. The physiological response of *Salix viminalis* irrigated with leachate is studied by Euan Brierly and James Dewitt and co-workers. At the same university Peter Randerson and co-workers are active in the boundary of wastewater treatment, wetland, and SRP willows for energy. Substantial work has been put into studies on horizontal subsurface flow beds planted with willows for small-scale wastewater treatment. Such constructed wetlands, planted with willow and acting as biofilters, are seen as a cost-effective method of disposal of farm slurry and other effluent, avoiding the risk of pollution of watercourses. The use of farm slurry on willows is also being evaluated at Cranfield University (Sean Tyrrel, Ruth Copeland and co-workers) within the project “Nitrate leaching and biomass production from SRWC on dairy farms” aiming at quantifying nitrate leaching as a result of varying application rates of slurry. That result should be directly applicable to the use of sewage sludge in SRPs.

Substantial research activities in the field of SRPs and wastewater have been conducted by Queen’s University Belfast, Department of Applied Plant Science, by Dawson, McCracken and co-workers. Their work has mainly focused on plant diseases (see above in “Management”), but Queen's University also participated in the large EU-funded project “Biomass Short-Rotation Willow Coppice Irrigated and Fertilised with Municipal Wastewater” (BWCW) together with the Swedish University of Agricultural Sciences (SLU; Perttu and co-workers), the Swedish Institute for Infectious Disease Control (SMI; Stenström and co-workers), Agricultural University of Athens (Greece; Mavrogiannopoulos and co-workers), together with several commercial enterprises (SWECO VIAK AB; Kenth Hasselgren, A&B Backlund ApS; Arne Backlund, WRc plc; Drusilla Riddell-Black, and coordinated by Svalöf Weibull AB; Stig Larsson). Although finalised in 2002, results from the project is still being evaluated and reported, and the project draw very much attention to the concept of wastewater irrigation of SRPs. The project was very broad in its scope and covered plant physiology, pest occurrence, biomass production, build-up in the soil pool or leaching of elements to groundwater, business economy, and technical issues. Experiments on wastewater irrigation of SRWC were established in four European countries (France, Greece, Sweden, UK) (Larsson *et al.*, 2003). There was a range of differences in soil and wastewater types, but the willow clone used was the same, i.e. *S. viminalis*, “Jorr”, which was developed for north-European climatic conditions. The results concerning nitrate leaching in the groundwater indicated differences that were not only correlated to the N amounts applied but also to the climatic and soil conditions in the different areas. The release of dinitrogen oxide (N₂O) from wastewater irrigated willow SRP has been extensively studied within a Swedish national project funded by the Swedish Energy Agency (STEM, Klemedtsson, University of Gothenburg; Aronsson, SLU, Uppsala and co-workers). Within that project the long-term (i.e. over several years) net fluxes of N₂O were measured using micro-meteorological techniques (eddy covariance) and a diode laser for 10-Hz measurements of air N₂O-concentrations above the canopy. The results from the project show significant but not alarmingly high emissions of N₂O. The project is partly still running (Aronsson, SLU, Uppsala) aiming at quantifying N₂O-emissions as a function of wastewater application rates, and biomass growth. In the same project leaching of N to groundwater was also monitored, and long-term variations in leaching have been quantified. Hardly any other projects related to wastewater irrigation of SRPs and emissions to air can be found. Another project that examined nitrate leaching took place in Belgium “Tertiary waste water treatment using short rotation willow coppice in Belgium” (funded by the Walloon Region, conducted by the University of Louvain). The results suggested very low nitrate levels in the groundwater but the N application rates were also relatively low compared to conventional practices. It was suggested that the irrigation loads should be increased for better treatment efficiency. Another effort in quantifying leaching and gaseous losses after irrigation with wastewater in SRPs with willow for an

environmental friendly and sustainable practice is conducted under the EU LIFE Environment project “Sustainable wastewater purification in Estonian small municipalities”.

From all the above-mentioned projects, it was concluded that an important issue related to wastewater irrigation of SRPs is the possibility of monitoring and controlling the irrigation loads, and to monitor the environmental impact of it. There are some different approaches to monitor and adjust irrigation loads by use of different types of soil sensors. Within an ongoing EU-funded R&D project WACOSYS (“Monitoring and control system for wastewater irrigated energy plantations”) the use of FDR (Frequency Domain Reflectometry) probes by SENTEK (“EnviroSmart”) are tested for real-time monitoring of soil moisture. This should enable adjustments of irrigation loads to prevent substantial leaching of elements beyond the rootingzone of SRPs supplied with wastewater. The project is coordinated by HYDRO-AIR GmbH (Germany) and involves several SMEs and RTD organisations; BIOAZUL S.L. (Spain), STAB Tratamento de Águas e Biotecnologia LDA (Portugal), Munitsipaalasutus Karjäär (Estonia), Antonio Ramos Fernandez (Spain), Profactus Recycling & Heating BV (The Netherlands), Estonian Agricultural University (Estonia), Warsaw Agricultural University (Poland), and TTZ Bremerhaven (Germany).

The European Commission supported the “Med-Reunet” project (ICA3-CT-2002-50002) aimed to generate strategies, technologies and management practices for local, safe, publicly acceptable, economically feasible and sustainable reuse of treated wastewater with the involvement of European, Mediterranean and world experts. “Med-Reunet II” continues the main objective of the Med-Reunet project (ICA3-CT-2002-50002) of consolidating a highly experienced working group in the Mediterranean basin in order to enhance co-operation between European and Mediterranean authorities, National and local institutions, policy makers, academic experts, professionals, end users, and others involved in the waste water reclamation and reuse, partly examining solutions for the safe reuse of wastewaters in general and the implications for use in SRPs in particular. The hygienic impact of wastewater irrigation of ordinary agricultural crops has been thoroughly studied in many countries and by numerous research organisations and teams. These studies have resulted in several guidelines on hygienic issues related to wastewater irrigation of agricultural crops. However, the sanitary aspects of wastewater irrigation of SRPs and other non-food crops have been far less studied. Some of the studies of agricultural crops are directly applicable to SRPs, e.g. spreading of pathogens by aerosols produced by spray irrigation. In Sweden, the hygienic risks associated with wastewater irrigation of willow SRPs was thoroughly investigated a few years back in the project “Hygienic aspects of wastewater irrigation of energy willow plantations–investigations at three full-scale facilities” (Anneli Carlander, SLU, Thor Axel Stenström, SMI, Ann Albihn, The National Veterinary Institute in Sweden, SVA, and Kenth Hasselgren, SWECO VIAK AB). The cooperation between SLU, SMI and SVA is still active and several publications are in progress on wastewater irrigation of SRPs and its sanitary implications.

As regards the use of sewage sludge and similar organic waste products as fertilisers in SRPs, much research concerning the environmental effects has been carried out in Sweden and UK, countries where such practices are widely adapted. The project “Application of sludge and wood ash mixtures to *Salix* on agricultural soils: Effects on biomass production, fuel quality and heavy metal status in the soil”, financed by STEM (P12302-1), conducted by SLU, investigated among others the nutrient and heavy metal fluxes in the soil-plant system after sludge applications within the legal national limits (Dimitriou *et al.*, 2006). It was suggested that heavy metal accumulation in the soil is within the legal limits for such applications in Sweden and that especially for Cd, which is considered the most problematic among the heavy metals, a decrease in the soil would be expected due to the uptake of Cd in the willow

shoots. Potential phosphorus accumulation in the soil needed more evaluation. Similar work for UK conditions with more focus on nutrient dynamics was conducted under the project “Nutrient dynamics and growth at a coppice biofuel site”, conducted at the School of Geography, Univ. of Leeds by E. Sagoo, funded by Kelda, estimations of the input and output and the soil accumulation of all the above-mentioned elements were conducted (Sagoo, 2004). An accumulation of P at the soil surface was observed, thus increasing the risk of P loss in surface runoff. Research on the environmental issues of sludge applications on willow SRPs has been conducted in DARD Northern Ireland by Dawson and his group, evaluating the effects of sludge use among others on biodiversity, bioremediation, water relations. Research on the use of willow for bioremediation of sludge-amended fields grown with willow SRPs are conducted in the Univ. of Nottingham by Young’s group under the “PASS” project (Phytoremediation of Arable Sludged Soils) and by Dickinson’s and Lepp’s groups at the School of Biological and Earth Sciences, Liverpool John Moores University. Pulford’s group at the University of Glasgow has worked within the EU funded BIORENEW project, with the remediation of sludge-amended land with willow SRPs.

4.5 Economy

Research related to SRP economy and profitability has been generally conducted in the countries where there are established commercial SRPs, e.g. Sweden, UK, Poland etc. Consequently, research related to the economic aspects of SRPs applied with wastewaters or sewage sludges is even scarcer. In absence of extensive research programmes and projects for the economic aspects of SRPs, we will in the following text try to refer to the economic aspects of SRP cultivation concerning the different management steps, to the research being currently conducted in different countries and to give some ideas of the results of this research.

A work by Ericsson *et al.*, (2006) shows that the production costs of SRPs in Poland is considerably less than the northern European countries (Sweden, UK, Denmark) (7 €/MWh instead for 12-15 €/MWh), due to lower labour costs. At the current price of wood chips (on average 8 €/MWh), SRPs with willow in Poland are less profitable than wheat but more profitable than barley. It should be noted, that willow is more profitable than both wheat and barley assuming the higher wood chip price of 13 €/MWh. A detailed description of the costs involved in SRPs grown with willow in Sweden and the percentage of costs for each management practice reveals that fertilisation and transport to district heating plant costs equals to 19 and 23%, respectively, of the total cost (Börjesson *et al.*, 2003, project financed by STEM P11666.). These costs are the ones that would be drastically reduced when irrigation with wastewater is applied, since most of the district heating plants, at least in Sweden, are not located very far from the wastewater treatment plants and the adjacent willow fields, which gives a good idea of the economic advantages after implementation of such systems. More detailed research on the economics of using willow SRPs for purification of wastewater is presented in Rosenqvist *et al.*, (1997) and Rosenqvist and Dawson (2005). There it is indicated that costs related to establishment of SRP irrigated with wastewater, e.g. pumps, ponds and pipes, and costs related to e.g. partly building of conventional wastewater plants are significant. Furthermore, high applications rates per hectare per year, long irrigation seasons and larger SRP areas keep the costs down. Concerning landfill leachate applications on willow SRPs for Swedish conditions, similar conclusions in relation to the profitability of such treatment systems were extracted (Rosenqvist and Ness, 2004). A good description of the viability of multifunctional willow SRPs (including irrigation of wastewaters and taking into account the environmental benefits of such systems) was conducted under the project

“Potentialen av multifunktionella bio- energisystem - odlingssystem av perenna energigrödor i Sverige, del 1” (in Swedish “Potential of multifunctional bioenergy systems – cultivation systems of perennial energy crops in Sweden, funded by STEM, project P12293-1). Concerning economic calculations for other species used as SRPs, Martin *et al.*, (2004) have done economic analysis of short rotation poplar crops in west central Spain. The economic calculations indicated a positive economic return for estimated biomass production of 22 t DM per hectare obtained from the first harvest. Also for *Eucalyptus*, Luger (2003) found similar profitability for coppice SRPs. In a number of the above-mentioned projects for management and of SRPs, economic calculations have been made in parallel to the main aspects of research, and therefore more information can be found in the different project reports.

Other research projects that have been conducted having a more broad perspective on the economics of bioenergy systems (including therefore indirectly and partly economic aspects of SRPs) are the following: “VIEWLS – Clear Views on Clean Fuels, Data, Potentials, Scenarios, Markets and Trade of Biofuels”, funded by EU NNE5-2001-00619, comparisons of energy crops production costs in NMS (*Miscanthus*, Willow, Poplar, sugar-beet); “EU-BIOTECH - Development of portfolios of bio-energy projects in selected countries of Central and Eastern Europe”, funded by EU DG TREN NNE5/2001/143, Reports on biomass market prices in EU and NMS countries; “EUBIONETI-II”, European Bio-energy Networks, established in 1995 and conducting many activities related to the reporting of biomass production costs within different EU countries e.g. reports on biomass market prices in EU; “ENERGY-FORESTS”, funded by EU ENK5-CT-2002-80647, including research on production costs of SRF on low-quality agriculture land in East / South EU for SRPs with willows and poplars; “RENEW”, EU funded SES6-CT-2003-502705, mission to prove different concepts of fuel production from biomass including the analysis of the biomass potential in Europe, the life cycle assessment from well to tank, technical and economic assessment of available production routes for BTL fuels from lignocellulosic biomass including SRPs; “ENFA (European Non-Food Agriculture)”, EU funded SSPE-CT-2005-006581, with the aim to establish a dynamic agricultural and forest sector models for the integrated economic and environmental assessment of non-food alternatives in European agriculture and forestry. The ENFA project will integrate engineering science and micro economic analysis for major non-food production lines with traditional agricultural and forest sector analysis across Europe. The proposed analysis will be intensively linked to many completed and ongoing European research projects and will join leading research institutes in the non-food area.

5 ANALYSIS AND IDENTIFICATION OF GAPS OF THE CURRENT KNOWLEDGE OF SRP FOR WASTEWATER TREATMENT

5.1 *Suitable tree species*

The suitability of the tree species that should be used as SRPs irrigated with wastewater or applied with sludge depends on the combination of a series of factors concerning both the suitability of cultivation of each species as SRPs and the response to wastewater applications. For instance, as suitable SRPs, the species should have high performance in terms of high biomass produced under specific climatic conditions, should be easy to manage (harvest etc) and should not be susceptible to pests and other diseases (more concerning this aspect will be commented in the next chapter, see below “Management”). While irrigated with wastewater, a suitable species should additionally perform well under these special circumstances, therefore it should have the ability to tolerate, take up or retain different hazardous compounds contained in the wastewaters/sludge (e.g. nutrients in excess and heavy metals), it should be tolerant to anoxic conditions into the root horizon (in case of e.g. high irrigation rates), etc. In this chapter, we will only analyse and identify the gaps of current knowledge concerning factors that do not include aspects related to management, environment and hygien. These will be further analysed in other chapters.

One general observation after a revision of the projects concerning SRPs and wastewater applications reveals that most research involves the use of willow species (*Salix* sp.), and that research with other species is considerably less compared to *Salix*, especially concerning large-scale experiments under field conditions. This is of little surprise since short rotation willow coppice is the only SRP cultivation widely used in Europe for production of biomass on agricultural soils and consists almost 100% of SRPs cultivated for production of energy. Since in most cases the cultivation of willow SRPs has been successful in terms of establishment, management etc., the existing systems have been used almost solely for the irrigation of such plantations with wastewater. Consequently, the use of willows in SRPs irrigated with wastewater has prevailed instead for other species that could be equally suitable for such practices. This does not necessarily mean that the knowledge for other species is limited, although surely not in the extend of the current knowledge for short rotation willow coppice, but the existent fields and knowledge that can be directly used for irrigation of wastewater gives little space for use of other species. Thus, although difficult to predict, the use of willows as the species for irrigation with wastewater will probably be the most popular in the future as well. The gap of knowledge in use of other species than willow irrigated with wastewater can be surpassed by the introduction of other species for large-scale SRP plantations. This of course is related to other aspects, as existing market demand, which will be decisive for the introduction of such species. In general, species of genus *Populus* are known to have high biomass production rates, exactly as it is the case for *Salix* sp. Reports presenting related research with poplars have given in many cases very high biomass production rates, which in many cases cannot be met in “real” situations and the result of small-scale plots cannot easily be extrapolated to large commercial plantations. This gap is valid not only for poplars but also for willow outside its present area of commercial cultivation, and for eucalyptus. Although the current reports about biomass production are more realistic, unusually high growth rates reported in the past create uncertainty (especially after some failures in achieving those rates) to the economic calculations and to the management practices and indirectly to the wide introduction of SRPs, which in turn lead to

limited use of species like poplars and eucalypts in SRPs, even in areas such as southern Europe, where it is proved that these species perform better than willow. Efforts in southern Europe for introducing other species that could grow better, as black locust (*Robinia pseudoacacia*) have not been very successful, mainly due to management problems. However, during the last years organised efforts for actively supporting research on other than willow species (see above efforts in e.g. UK research on poplars) can lead to the commercial introduction of other species. A gap related to the previously mentioned gaps in knowledge on the suitable tree species aspects, can be considered the lack of availability and knowledge of willow clones that can be successfully used in the variety of European climates. As it was mentioned before, in the FAIR-CT97-3947 project, a willow clone that was developed for Swedish conditions was used in the experimental countries (see above) and had as a consequence lower biomass production than expected in the south European countries due to susceptibility to pests and draught of the clone ("Jorr"), which was not adapted to the climate. Problems of rust in the UK have been also reported and attributed to imported plant material. This is an indication that the current breeding programmes must develop more suitable plant material for broader climatic ranges. Research adjusted on the specific climatic conditions for a potential area planted with SRPs, possibly in conjunction with the use of local species that perform well in terms of production, could result to the introduction of more suitable species/clones.

Research related to the introduction of suitable species/clones that would be cultivated as SRPs in large-scale plantations, have not taken into account some plant characteristics that could be proved very useful for the best practice of wastewater irrigation/sludge application to such plantations. For instance, the focus of identifying, developing and introducing willow clones that could accommodate increased heavy metal uptake/retention is limited. The same could be mentioned for clones that can tolerate increased amounts of heavy metals, salt and nutrients in unbalanced proportions (potentially causing growth disturbances), and will not show detrimental effects after high rate applications of waste products. Specific breeding or in some cases problematic genetical improvement of species could lead to better adapted performance under different local conditions. In addition, the suitability of poplars in SRP cultivation system is a topic that needs to be addressed; poplars resprout both from the stump and from the roots, and the latter sprouts may cause problems for the management and harvest following the first harvest.

In summary the following gaps were identified:

- Methods for scaling up and extrapolating yield from experimental to commercial scale of poplars, willows, and eucalyptus SRP for different European climate regions
- Selection and improvement of willow clones for climatic regions outside its present area of cultivation
- Selection and improvement of clones/provenances suitable for wastewater/sludge application
- Quantification of the problems related to root sprouts in poplar SRPs
- Suitability for cultivation in mixed stands and/or with beneficial co-plants

5.2 *Management*

SRPs are commercial crops established in large-scale fields for production of biomass for energy for at least 15-20 years, at least when it comes to willow coppice plantations. Research about the management aspects for short rotation willow coppice plantations has been going on for at least 30 years. Therefore, and taking into account the commercial character of the crop, which implies best management techniques achieved to reach cost-effective management practices, the gaps in the knowledge for management techniques of SRPs with willows are limited. One question mark could be set about the longevity of such plantations, i.e. for how many years can a willow SRP remain productive in terms of biomass, especially when it is irrigated with wastewater. This can only be answered by long-term experiments investigating growth in commercial plantations. For the other potentially used species in SRPs, the gaps in knowledge are more evident since e.g. SRP poplar or eucalyptus are not widely used as commercial crops, and in most cases only experimental plots exist. For those species, the improvement of management techniques for cultivation in short rotation coppice systems is in a way undergoing, since extensive research has been conducted having focus on other cultivation systems that aimed in different end-product than biomass for energy, e.g. pulp wood, veneer etc. It is obvious that the cultivation methods and management techniques when it comes to biomass production for energy should be different. The gaps of knowledge in terms of management become more apparent when referring to the application of wastewater/sludge, which is a new technique not widely used. For this, and considering that in most cases in reality commercial SRPs used for application of the above-mentioned waste residues, the gaps in knowledge need to be divided into two parts, namely the management gaps of SRPs in general and the gaps in knowledge related to management aspects involving wastewater/sludge activities. In this report, we will try to refer separately to both these aspects. Some cases of gaps of knowledge where the management aspects are closely related to the environmental impact of such practices will be described in more detail in the respective chapter below.

The existing plantation design with the current planting density proposed for short rotation willow coppice (from the 17500 cutting per ha proposed some 5 years ago to 13000 per ha nowadays) indicates a steady reduction of the number of cuttings per surface area, as a result of improved clone material that has resulted in better individual plant growth. The planting method in planting willow cuttings in double rows is a unique characteristic of SRP willow plantation which is a result of the need for mechanised treatment of these plantations, e.g. for harvesting with the specially designed machine that their shape makes them able to drive within the rows and conduct the management of the plantation, e.g. harvest one double row at a time or apply fertiliser. The same management techniques could be implied for other SRP species, e.g. poplars and eucalyptus, but for implementation of large-scale SRPs, these methods should be adapted to the special characteristics of each species. For instance, the fact that eucalyptus might grow faster and produce higher biomass rates than willows might not be encouraging for adapting either the double row system or the density for willows, since problems while e.g. harvesting are very possible to occur, as indicated in some related projects conducted (see above). Therefore, specialised management techniques that will aim to mechanised solutions for each species used for SRPs would contribute to better prerequisites for large-scale implementation of SRPs. This applies not only for the plantation design and densities, but also for management practices as the establishment of SRPs (plantation machines, cutting sizes etc), the storage of wood biomass, the termination techniques etc. Different plant species respond in a different way to management techniques when planted in high densities, and therefore an approach adapted to each species should be aimed for achieving high biomass production. Research on these aspects can be improved

only if large-scale experiments are established, preferably in commercial plantations, in order to improve all management aspects involved. This can be expected with the implementation of SRPs with poplars or eucalypts, an improvement in management aspects is expected. The fertilisation needs of such crops, must also be specified and be adapted in connection to the possible environmental risks involved after such practices, namely the leaching of nutrients (N, P) in the groundwater. These recommendations must take into account the cultivation manner as SRPs, which is different than the conventional for hardwood species, and the fact that the final product (e.g. chips for energy) is of lower value than e.g. pulp, veneer etc. A weakness in the management techniques of willow SRPs can be considered the fact that there are no exact recommendations for specialised chemical management for SRP species, e.g. willows, in a national or European level; there are no proposed chemicals for pest management in willows that are valid throughout all countries where willow SRPs exist. This of course is not due to gaps of research related to this aspect but more a legislative issue, which however adds to the confusion for a satisfactory plantation management. The same applies for SRPs with other species as well.

The gaps of knowledge concerning the management issues when irrigation with wastewater occurs include issues that involve the technologies for wastewater applications. This matter will be analysed in the next part of this document. In many cases as well, management practices of irrigation amounts and methods are related to the involved environmental impact, therefore a more detailed analyses will take place in the respective chapter of this document. An aspect that is usually considered as a management uncertainty for SRPs irrigated with wastewater is the exact amounts of wastewater that can be applied on the different SRPs, which will achieve best growth and simultaneously minimal environmental consequences. Due to the many factors interfering for best performance of the system while such practices occur (soil, plant, climate, and their interactions), the irrigation levels need to be adjusted site-specifically. For each case, different amounts should be applied, and the decided amount should be based on the environmental consequences caused by such practices. Another management uncertainty is related to the lack of exact guidelines concerning the quality of the irrigation water. Although there are regulations concerning the maximum levels allowed of certain compounds in the different wastewaters, there are no guidelines suggesting e.g. if a pre-treatment is needed, and in that case which pre-treatment method should be proposed. The tolerance of the different species used in SRPs to certain hazardous compounds varies and such differences can be also evident between clones of the same species (e.g. *Salix* clones). Therefore, no common regulation can be made that would suggest a certain pre-treatment method in case of a wastewater with known origin. The differentiations in concentrations of hazardous compounds in wastewaters with common source have also contributed to this lack of clear recommendations. Furthermore, due to the diverse responses of the different species and to climate differences, certain pre-treatment method procedures are difficult to be set.

In summary the following gaps were identified:

- Planting density and -schemes of different species
- Long term productivity in SRPs of different species/clones
- Harvest interval
- Harvest technique
- Weeding methods
- Fertilization requirements
- Salt and sodicity tolerance
- Tolerance to water logging
- Empirical models for system performance

5.3 Technologies for wastewater application

The current knowledge concerning the application technologies of wastewater to SRPs is not specialised only for SRPs, but irrigation systems that are widely used for wastewater irrigation of common agricultural crops taking into account the risk for spreading of diseases are generally adapted. Therefore, in many cases the use of sprinkler irrigation systems are avoided and instead applications close to the plant and soil surface are preferred. In most cases, drip irrigation systems have been considered to be more appropriate for such practices, despite the higher establishment costs involved for such systems compared to less technically advanced solutions. The exact type of drip irrigation system that would be used for best performance depends on many factors and is in many cases difficult to decide in advance, since different companies offer different systems that need to be evaluated first under “real” field conditions. It has been also proved that the existence of good filters to avoid large particles in the pipes is helpful for good performance. The pipes should be positioned in field places where they would remain as unaffected as possible by mechanical activities; in the case of willow SRPs, where the double-row system is used, the pipes are placed within the double-rows to avoid damage while harvest. It is then important that the cutting height is sufficiently high to avoid that the irrigation pipes are cut and chipped. This might cause very costly searches for leaking pipes and maintenance. A question that arises is concerning the necessity of having one pipe in every double row or if it would be satisfactory to use one pipe every two double rows to substantially reduce the establishment cost, but not the efficiency of the system. Problems related to root clogging are avoided by the adaptation of proper irrigation pipes, and this usually adds to the total cost. Therefore, cheap solutions to avoid clogging of pipes should be adapted. An issue that is under investigation is the “life expectancy” of such irrigation systems, since some mechanised activities in the SRP field (e.g. harvest) can cause damage. It can be hypothesized that softer (and therefore cheaper) irrigation pipes, which would therefore be cost-effective to be replaced more frequently, could in some cases be preferable than harder ones, in cases where damage from mechanical activities occurs. The frequency of the drips on the irrigation pipes and their relative distance from the plants is also a research aspect that has not adequately been answered from the current research activities. From the current knowledge it cannot be assumed that the drips should be placed on the pipes in the same frequency as for the plants, and it could be tested if longer distances between the drips result in worse results in terms of wastewater availability to the plants. In such a case, adapting a wider interval between drips would enable cost reductions.

In summary the following gaps were identified:

- Distance between drippers in drip lines
- Clogging of pipes by roots and particles - life expectancy
- Water distribution pattern in the soil and leaching
- Solutions for proper wastewater pre-treatment (storage, filtering)

5.4 Environmental and hygienic impact

The environmental and hygienic effects of wastewater irrigation and sludge application in SRPs have been under extensive investigations due to the nature and the content of these waste residues. Both wastewater and sludge contain macro- and micronutrients beneficial to the plants, but also a series of hazardous compounds as heavy metals, organic compounds, nutrients in excess or pathogenic organisms which could cause health problems. Research on the hazardous effects of such practices to human and nature is of vital importance if wider applications of such practices are to be conducted in the future. In the next sections, we will try to describe separately the gaps of knowledge of research aspects related to each of the components affected and the hygienic risks after such applications.

5.4.1 Leaching of elements to ground- and drainage water

The leaching of elements to groundwater after applications of wastewater on SRPs has been under investigations within many relevant projects. Due to the high concentrations of N (and in some cases P) in most of the types of waste residues applied in SRPs, the research has been concentrated on e.g. nitrate concentrations in the groundwater after wastewater irrigation. From the results until now, it is evident that N leaching is “case specific” and the type of wastewater, the irrigation load and method, the soil conditions, the plant growth achieved, the climatic conditions, and their interactions, are responsible for leaching levels in every case. Therefore, it is difficult to predict the nitrate leaching beforehand, even if the irrigation load is very moderate. In order to avoid negative effects on the groundwater and drainage water quality, good monitoring of the nitrate levels is needed to estimate the N load that will not cause substantial leaching if applied to SRPs, which implies research using small scale pre-trials in the area under question before the implementation in a larger scale. The same applies for the leaching of phosphates and of organic compounds to the groundwater, although this is considered of minor importance, mainly due to the low initial concentrations in wastewater (which in most cases has been under some kind of P-reduction treatment or reduction in organic substances). In general, it should be mentioned that most research concerning SRPs and leaching has been conducted on willows, and more research trials with poplars and eucalypts should be initiated in order to gain experience for these species as well.

Regarding the sludge applications to SRPs and the potential leaching involved after such practices, the element that is usually under investigations for leaching is P, since P loads after sludge applications within the legal limits usually are much higher than the amounts that will be taken up by the plants. In this case, there could be substantial leaching of P, considering the accumulated loads in soil and the concentrated and repeated sludge applications (in practice, a sludge load equal to 4 years' is applied every time after harvest of SRPs, and a moderate load of P in e.g. Sweden can be up to 88 kg/ha, and in other countries it can be considerably higher). Opinions regarding the risk of P losses after sludge application are rather contradictory (Dentel, 2004; O'Connor *et al.*, 2005), and this inconsistency is reflected in the limits set by the legislation in different countries. The permitted supply of P by sludge fertilisation is far higher in other European countries than in Sweden, and in the USA, sludge applications basically depend rather on N amounts than on P, although concerns about the P supply have been raised (Morsing, 1994; Shoher and Sims, 2003). A supply of P based on plant requirements would imply a more sustainable approach. In that case, however, the plant-available P in the soil would be more appropriately used as a regulator of the P supply when applying sludge. Plant-available P in sludge is approximately estimated to be ca. 50% of the

total P supplied, and is strongly related to the origin of the sludge (Shober and Sims, 2003), to the available P supplied via the sludge, to the soil's content of available P and to soil type. The soil content of available P, and the soil type, must therefore also be taken into account if plant-available P is to be used to regulate sludge applications. More research into the P supply after the application of sludge in SRPs is therefore needed to assess the sustainability of such practices. Leaching of heavy metals is not thought to pose threats to the environment, since after sludge application most of the heavy metals are bound to the organic matter of sludge or to soil particles and are becoming highly immobile and unavailable even to plants. However, the loads of heavy metals are increased in the soil pool and this needs to be investigated (see next chapter).

In summary the following gaps were identified:

- Long-term fate of applied P
- Leaching of N and P as a function of multiple factors in order to establish empirical models for predictions/optimisation of irrigation and/or sludge application
- Comparison between species concerning nutrient uptake and retention
- Proper monitoring approaches regarding N and P leaching

5.4.2 Build-up of elements in the soil pool

As mentioned above, the amounts of nutrients and heavy metals applied with wastewater and sludge to SRPs result in accumulation in the soil and potential leaching in case of excess loads applied (considering also other processes involved, e.g. losses to the atmosphere, immobilisation, mineralisation etc). Research related to environmental problems after applications of such waste residues has been concentrated on the accumulation of heavy metals in the soil pool, on the accumulation of nutrients such as N and P that can be later mineralised and cause extensive leaching, and on the increased concentration of salts after applications of wastewaters which inhibit plant growth (the problem is enhanced when wastewaters containing chloride, as e.g. landfill leachate, are applied).

In most countries, the maximum heavy metal loads applied with sludge are regulated by law, and so are the maximum allowed concentrations in sludge and the maximum amounts allowed in agricultural soils. In certain countries, e.g. in USA and UK, the application rates are adjusted only to maximum N or P amounts applied. Therefore, in general, and especially in countries where the heavy metal loads are not regulated, more research should look into the long-term effects of metal accumulation in soils, their potential uptake on plants and their potential uptake by food crops in case of a consequent cultivation after SRPs. For some metals, the total uptake in the plant shoots of a SRP per hectare basis can be considerable; this could imply that the maximum allowed metal loads applied with sludge could be higher. More research on this aspect could adjust the permitted heavy metal amounts with applications of sludge, which are usually the limiting factor. Possible effects on micro-organism populations in SRPs (in case of very high metal loads) should also be investigated since a series of processes can be affected with diminished micro-organism populations. The total amounts of P (even the permitted ones) should also be investigated, since it is not clear how these accumulated amounts (see above) will affect the sustainability of the systems in the long run, e.g. in terms of leaching. The N paths after high-load applications should be identified more in detail as well, to evaluate the N status in the soil and in the air (see next

session), and to avoid extensive leaching after N mineralisation enhanced due to the application of wastewater containing also micronutrients needed for microbial growth.

Toxicity symptoms on individual plants occur in some cases when high salt loads are applied via irrigation with wastewaters. This is more evident in dry areas where the dilution effect due to precipitation is limited, especially in the summer period when the irrigation takes place. The same can be observed when the initial amounts of not only nutrients as N, but also for compounds as chloride, sodium etc. are relatively high in the wastewater (e.g. landfill leachate). In such cases, the amounts of saline compounds should be regulated and pre-tests examining the tolerance of different species/clones should be used to identify the most tolerant once in terms of growth. The ability of different tree species to accumulate more P or heavy metals should be also tested for checking the most appropriate species under stress conditions.

In summary the following gaps were identified:

- Long-term fate of N and P applied via wastewater and/or sludge
- Quantification of P-losses from heavily P loaded soils
- Quantification of the variation between species/clones in uptake of N, P and a large number of heavy metals
- Quantification of changes in soil salinity and –sodicity after wastewater irrigation in dry regions
- Changes in soil structural properties resulting from input of sodium by irrigation
- Proper monitoring guidelines for farmers

5.4.3 Air pollution

Research on identifying air pollution caused by applications of wastewater and sludge in SRP is, as mentioned above, limited (see above 4.4). The most hazardous gas which is closely under investigation for release in the atmosphere after such practices is dinitrogen oxide (N_2O). The levels of the released amounts in the atmosphere should be checked with varying application loads of wastewater in different geographic areas in order to obtain a more complete picture of the released greenhouse gas emissions. The same should be applied also for methane (CH_4) and CO_2 , to cover a broader spectrum of the greenhouse gases, despite the high cost for research on these issues.

Also emissions of NH_3 following wastewater and sludge application should be measured in order to quantify the eutrophication potentially caused by the practice of wastewater irrigation.

In summary the following gaps were identified:

- Quantification of the emissions of N_2O and NH_3 after wastewater irrigation in various regions and at various irrigation intensities
- Quantification of the CO_2 balance of conventional and wastewater irrigated SRPs
- Proper management against smell nuisance

5.4.4 Hygienic risks

The hygienic risks after applications of wastewaters or sludges on SRPs are considered in general lower than the respective ones when edible crops are cultivated. SRPs products are not consumed as food or fodder and that eliminates the risks for entrance of hazardous compounds in the human food chain. However, the risks for spreading of viruses and other pathogens should not be underestimated, and the recommendations set by FAO and WHO must be considered. Beyond that, further protective measures should be taken in cases where there are uncertainties for the hygienic effects after applications of wastewaters that could be hazardous to the environment; although the soil-plant system is thought to offer good retention of viruses and pathogens, after application of untreated or slightly treated or newly collected wastewater, the risks can be higher. After irrigation with wastewaters that contain higher amounts of pathogens, research concerning the concentrations of pathogens in the groundwater under field conditions should be conducted, to assure the minimal hazards under different soil conditions. Additionally, the different pathogens in the groundwater should be identified and evaluated for possible hazardous effects to human health. The soil type is thought to be of high importance for leaching of pathogens in the groundwater, therefore different soil types and wastewaters containing different levels of pathogens should be evaluated in relation to the leached pathogens in the groundwater. The application of sludge on SRPs results in fields that are more or less covered with a layer of a mixture of organic matter and sludge which under special circumstances (e.g. carrying from animals) can be spread in the surroundings via zoonoses. The risks from such events could be closer evaluated. Finally, in cases where other than drip irrigation is used, e.g. sprinkler irrigation, the potential hazards of virus and pathogen spreading to the environment due to wind etc, should be further evaluated.

In summary the following gaps were identified:

- Quantitative risk assessments for a range of pathogens in field situations
- Groundwater contamination
- Secondary transmission (zoonoses)
- Transmission of pathogens in aerosols formed at sprinkler irrigation
- Monitoring schemes for early warnings of elevated risk

5.5 *Economy*

The gaps of knowledge concerning the economic issues of SRPs irrigated with wastewater are related mostly to the existence of a viable market for SRPs in the different countries. It is generally difficult to compare cost/benefits from an activity that is only theoretical, and surely the cost of such systems will be much lower if an established market exists. Therefore, a better evaluation will be achieved when SRPs will be economically viable in all countries referred. In countries where SRPs is an established crop, SRP production costs are close to wood fuel price and in many regions SRC is competitive to grain production, and therefore continuous comparisons with the other potentially used agricultural crops should be conducted. SRPs with willow have thus far been one of the most competitive new renewable energy source and the conditions are good for a substantial market growth. However, from the energy supply perspective it should be regarded in long-term perspective. The development of modern biomass energy systems is at a relatively early stage with most of R&D focussing on

the development of fuel supply and conversion routes. One example is the willow production for energy purposes in SRPs. SRP cultivation with willow is still an emergent agricultural activity with a small land claim. As a result, the cost of short rotation coppice is expected to decrease in the future due to scale effects from an expanded cultivation area, and a development of machineries, breeding, and increased knowledge. There is a need to analyse the prospects of cost reductions considering an ideal future situation with large-scale, well-established SRP market in Europe. There is also the need for comparisons of different energy crops in different regions with the same method which will allow the direct comparisons for the different energy crops in different regions. In most cases for applications of wastewater to SRPs, the wastewater used is mostly treated. Other types of wastewater used from earlier stages of conventional treatment, e.g. before P precipitation would offer greater benefits in relation to the lower costs in the conventional wastewater treatment plants. Such aspects have not been included in the earlier calculations and publications. In general, the parallel environmental effects cannot be accounted in economic terms and therefore are not accounted for in the economic calculations, giving less value to the use of SRPs for treatment and utilisation of wastewaters and sludges. The same is valid for the environmental hazards implied by such applications.

In summary the following gaps were identified:

- Quantification of cost reductions in cultivation of SRPs following scaling up of the cropped area
- Quantification of the additional expected profit from SRPs needed for making farmers invest in SRP cultivation
- Cost/benefit analysis of SRPs as the only P treatment method
- Quantification of the costs of environmental damages potentially caused by improper design and management of SRPs for wastewater treatment
- Cost/benefit analysis of SRPs for recycling of P in the society
- Cost/benefit analysis of SRPs for remediation of metal contaminated arable soils

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