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Environmental effects of energy crop cultivation in Sweden—I: Identification and quantification

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Abstract

This paper presents an analysis of how energy crop cultivations in Sweden, consisting of short-rotation forest (*Salix*) and energy grass (reed canary grass), can be located and managed to maximise environmental benefits. The overall conclusion is that substantial environmental benefits, ranging from global to site-specific, could be achieved when traditional annual food crops produced with current agriculture practices are replaced by dedicated perennial energy crops. The emission of greenhouse gases could be reduced by reduced carbon dioxide emissions from organic soils, by reduced nitrous oxide emissions caused by the use of fertilisers and through accumulation of soil carbon in mineral soils, which also leads to increased soil fertility. Nutrient leaching could be reduced by using energy crop cultivations as buffer strips along open streams and wind erosion could be reduced by using *Salix* plantations as shelter belts. Cultivation of *Salix* and energy grass can also be used to purify municipal waste, such as waste water, landfill leachate, and sewage sludge. Furthermore, the content of heavy metals in the soil can be reduced through *Salix* cultivation. The biodiversity is estimated to be almost unchanged, or slightly increased in open farmland. These environmental benefits, which could be achieved on up to 60% of current Swedish arable land and last for 25 years or more, will increase the value of the energy crops. The economic value of these benefits is calculated in Part II of the analysis, which is presented in a second paper. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Energy crops; *Salix*; Reed canary grass; Cultivation; Environmental effects

1. Introduction

Replacing fossil fuels with biomass leads to global environmental benefits such as reduced emissions of greenhouse gases. However, not only the use of biomass could lead to benefits for the environment, but also the production of the biomass. This paper will show that when traditional annual food crops are replaced by dedicated perennial energy crops on Swedish arable land, negative environmental effects from current agriculture practices such as erosion, nutrient leaching and the emission of greenhouse gases, may be reduced. Similar conclusions have been drawn in earlier studies concerning, for example, perennial energy crop production in the USA (see e.g., Tolbert [1]; McLaughlin and Walsh [2]; Kort et al. [3]; Grigal and Berguson [4]; Bransby et al. [5]). Energy crop systems can also be used to purify municipal waste, thus reducing negative impacts from the community. Furthermore, the

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content of heavy metals in the soil could be reduced through cultivation of short-rotation forest. These environmental benefits could increase the value of the energy crops, thereby affecting future market conditions for biomass.

In this paper, environmental changes are identified and quantified when traditional food and forage crops produced with current agriculture practices are replaced by perennial energy crops on Swedish arable land. This paper, which is based mainly on a literature review, represents Part I of the analysis, which is complemented by a second part in which an economic valuation of the environmental changes is carried out (see Börjesson [6]). Thus, this paper is a background to the second paper, which includes a more integrating synthesis. The purpose with the overall study is to analyse how energy crop cultivations in Sweden could be located and managed to maximise environmental benefits. Neither environmental effects arising from replacing fossil fuels by biomass nor environmental benefits from the reduced use of fossil fuels in perennial energy crop cultivation, in comparison to annual crop cultivation, are included in this study as such benefits have already been analysed in earlier studies (see e.g., Börjesson [7, 8]). The magnitude of the environmental benefits depends on, for example, geological and geographical conditions, while population density influences the amount of municipal waste that can be recycled on energy crop cultivations. Thus, the environmental impact is analysed on a regional basis and then aggregated to a national level. Since agricultural practices, the load of antrophogenic pollutants and the generation of waste, are changing over time, the potential impact of energy crop cultivation also changes over time. The time during which environmental advantages could be achieved is therefore estimated.

2. Methodology and assumptions

Energy crops included in this analysis are short-rotation forest (*Salix*) and energy grass (reed canary grass). In the north of Sweden, only reed canary grass is assumed to be grown for energy purposes as the climatic conditions are not suitable for *Salix* cultivation [9]. This situation can, however, change in the future if more frost resistance *Salix* clones will be available. The energy crop cultivations are assumed to be geographical equally distributed on current arable land used for perennial forage and annual food crop production [10]. Today, about 40% of Swedish arable land is used for the production of perennial forage crops, mainly ley, while about 60% is used for annual crop production. When perennial energy crops replace perennial forage crops (in Sweden normally clover-grass ley), the environmental changes are assumed to be small and are therefore neglected, except when the impact is particularly caused by the cultivation of *Salix*, e.g. reduced wind erosion and cadmium removal. In annual crop cultivation, which in Sweden is dominated by grain cultivation, ploughing is assumed to be undertaken annually, the average dose of chemical nitrogen (N) fertiliser applied is about 140 kg N/ha yr, and the average dose of chemical pesticides is about 1 kg active ingredients/ha [7]. Reed canary grass cultivation, harvested once a year, extends over 10 years, while *Salix* cultivation, harvested every fourth year, extends over 25 years. The biomass yield of *Salix* is assumed to be, on average, 10 tonne dry matter/ha yr, and of reed canary grass, 6.5 tonne dry matter/ha yr [7].

The environmental impact of energy crop cultivation varies between different regions in Sweden due to local conditions. Here, impacts are analysed for each county of Sweden (24 in 1996) and then aggregated to a national level.

Soil type distribution on arable land in Sweden is divided into four classes using the American soil classification system, regarding differences in physical and chemical properties of the soils (Table 1).

Cultivation methods in agriculture are changing, as well as the load of antrophogenic pollutants and the generation of waste. Thus, the time during which environmental impact could be sustained is estimated. This estimate is based on physical and chemical properties of the soils, environmental goals for future agricultural practices, recycling of waste and reduction of

Table 1
Soil type distribution (%) on arable land in Sweden [11–13]

Mineral soils			
Clayey soils*	Loamy soils†	Sandy soils	Organic soils‡
55	19	17	9

* Including sandy clay loam, silty clay loam, and clay loam. †Dominated by silt. ‡More than 20% organic matter

antrophogenic emissions, and prognoses of the possibility of attaining these goals.

The term "environmental change" or "changed environmental impact" is used here in a broad sense, as effects on soil, water, air, flora and fauna, and the recirculation and purifying of municipal waste, are included. Environmental changes when perennial energy crops replace annual crops identified in this paper have been divided into six categories: (1) greenhouse gases, (2) nutrient leaching, (3) heavy metals, (4) soil fertility and erosion, (5) municipal waste treatment, and (6) biodiversity.

The aesthetic impact of short-rotation forest on the landscape has not been considered here. Depending on the nature of the surrounding landscape, and the design of the cultivations, *Salix* cultivation is assumed to have the possibility of causing both positive and negative effects on the landscape [14]. Neither is the impact of *Salix* on tile drainage considered, which could lead to expenses. There is a great risk of damage to the tile drainage when *Salix* is cultivated, due to the deep *Salix* roots [15]. This risk has not been considered, as about two thirds of the total Swedish arable land lacks tile drainage [10]. *Salix* may also be grown in fields with old tile drainage, which has mainly served its function. *Salix* cultivations are assumed to extend over 25 years, which is about the same period of time as the technical life-time of a tile drainage system. If energy crops are to be cultivated in fields with new tile drainage systems, energy grass should be grown in preference to *Salix*.

Environmental benefits from the reduced use of chemical pesticides in perennial energy crop cultivation, in comparison to annual crop cultivation, is restricted to be included only in the category "biodiversity". No analysis of the reduced risk of, for example, ground water pollution has here been carried out due to lack of data.

3. Identification and quantification of environmental effects

3.1. Greenhouse gases

Greenhouse gas emissions from arable land can be reduced in three different ways when annual crops are replaced by perennial energy crops, through (i) accumulation of soil carbon (C) in mineral soils, (ii) reduced carbon dioxide (CO_2) emissions from organic soils, and (iii) reduced nitrous oxide (N_2O) emission caused by the use of fertilisers. Changes in the emissions of other greenhouse gases are estimated to be small and are therefore neglected.

3.1.1. Accumulation of soil carbon in mineral soils

The rate of change in soil carbon depends on the rate at which organic matter is added to the soil and the rate at which erosion and biological oxidation remove the organic matter from the soil [16]. The two latter mechanisms are substantially reduced if soil tillage is reduced or eliminated, which is the case when annual crops are replaced by perennial energy crops. Also, the input of organic matter from litter and roots to the soil is high in energy crop production. In an established *Salix* cultivation, 4.5–10 tonne dry matter/ha is recirculated yearly, of which about two thirds are litter and one third is roots [17]. Only a minor part, however, is converted into stable humus containing, on average, about 60% C, as most of the organic residues are decomposed within period of a few weeks up to a year [16].

Results from Swedish [17] and German [18] field trials shows that a vertical gradient of soil carbon is developed after a few years of *Salix* cultivation, with a higher carbon content in the top soil. No significant changes in the total content of soil carbon have yet been recorded, as these changes take place over a long period of time [16]. Long-term field trials with ley grass in Sweden, which could be comparable to *Salix* regarding changes in soil carbon [17], show an increased level of humus equivalent to 30–40 tonne C/ha, compared with food crops after 30 years [19]. To some extent, this difference could be explained by changes in cultivation practices, as the depth of ploughing is probably greater now than in the 1960 s, causing a higher dilution of soil carbon in food crop cultivation with frequent ploughing. Therefore, a change from annual to perennial crop production is estimated to lead to a somewhat lower increase in soil carbon content than the results of field trials presented above indicate.

An annual carbon accumulation in mineral soils of 0.5 tonne C/ha is assumed here, over a period of about 50 years. After that, the humus level is estimated to reach a new, higher, steady state of about 1–1.5 percentage points higher than today. This estimate is, however, uncertain and must be verified by long-term field trials. Changes in soil carbon storage also vary for different soils and locations due, for example, to soil texture, drainage, base status and climatic parameters [4]. The proportion of the total Swedish arable land where energy crop cultivation could increase the soil carbon level is estimated to be 55%. This is equivalent to the area covered by mineral soils (which amounts to about 90% of the total arable land, see Table 1) on which annual crops are cultivated today. At present, about 60% of Swedish arable land is used for annual crop production [10]. On the remaining 40%, where perennial forage crops are cultivated, no increase in the soil carbon level is assumed to occur.

As a comparison, Ranney and Mann [20] estimate that short-rotation plantations in North America increase the soil carbon inventories (excluding litter and roots) by about 10 tonne/ha over 20–50 years.

3.1.2. Reduced CO_2 emission from organic soils

When organic soils are cultivated, soil carbon is released by oxidation leading to a subsidence in ground level. In an initial phase when an organic soil is drained, a lowering of ground level is also caused by compression and shrinking [21]. The carbon loss is higher in annual crop cultivation than in perennial crop cultivation due to more frequent soil tillage. Results from Swedish investigations [21] show the subsidence rates are greatest when the crops are potatoes and carrots, 2–3 cm/yr, followed by grain 1–2, ley 1, and permanent pasture 0.5 cm/yr. Based on these results, a change from cultivation of annual crops to perennial energy crops is estimated to reduce the subsidence rate from, on average, 2 to 1 cm/yr. This is equivalent to about 7 tonne C/ha yr, as the density and carbon content of cultivated organic soils in Sweden are about 200 kg/m^3 and 35%, respectively [22]. This theoretical calculation has, however, not been verified by field trials [23]. *Salix* thrives best on organic soils consisting of fen peat (*Carex*). If the organic soil is composed of bog peat (Sphágnum), however, *Salix* is not a suitable crop due to the low pH of the soil. Thus, bog peat soil is more suitable for the cultivation of reed canary grass.

The reduced CO_2 emission from organic soils when cultivating energy crops is assumed to last, on average, 80 years after which the peat layer will have been dissipated by biological oxidation. A rough estimate is that the thickness of the peat layer, which can vary greatly both within a field and between different fields [21, 24], varies from a few decimetres up to two metres in Swedish organic soils, with an average of about 80 cm [22]. The proportion of arable land where energy crop cultivation could decrease the CO_2 emission by about 7 tonne C/ha yr, is estimated to be 5%. This is equivalent to the area covered by organic soils (which amounts to about 9% of the total arable land, see Table 1) on which annual crops are cultivated today.

3.1.3. Reduced N_2O emission from mineral soils

Nitrous oxide emission from arable soils is induced by the use of fertilisers. Loss of fertiliser nitrogen (N) as N_2O varies from almost zero up to 2%, due to differences between soils, fertiliser type, climate and land management practices [25, 26]. Since energy crops have a lower nitrogen demand than food crops, on average, about 50 kg N/ha yr [7], a change in land use from food to energy production is assumed to reduce the emission of N_2O. Regression analyses by Bouwman [27] show a statistically weak correlation between N_2O emission and input of nitrogen fertiliser. A rough estimate from this correlation is, however, that growing perennial energy crops instead of annual crops on mineral soils will reduce N_2O emission by, on average, 0.3 kg N_2O-N/ha yr. A similar estimate has been made by the National Swedish Environmental Protection Board [28]. This reduction is equivalent to about 40 kg C relative to the Global Warming Potential (GWP) of CO_2 over 100 years [29].

Apart from lower input of nitrogen fertilisers, the risk of N_2O losses in perennial energy crop plantations is assumed to be reduced due to the low availability of mineral nitrogen in the soil, as energy crops have a longer growing season and a more extensive root system than annual crops [28]. On the other hand, N_2O losses could be stimulated by the nitrogen-rich litter produced in *Salix* plantations and if the tile drainage were to be damaged by roots, leading to wet soils [17, 18].

The proportion of the arable land on which energy crop cultivations could decrease the N_2O emission is estimated to be 55%, which is equivalent to the mineral soils on which annual crops are cultivated today. Changes in N_2O emission from organic soils are not considered here as the input of nitrogen fertiliser is assumed to have a smaller impact on the N_2O emission from these soils, than from mineral soils. The content of organic nitrogen, for example, is much higher in organic soils than in mineral soils, and thus the rate of nitrogen release in organic soils may have a greater impact on the N_2O emission.

3.2. Nutrient leaching

When perennial energy crops replace annual crops, the nutrient leaching is reduced. Nutrient leaching from annual crop cultivation could also be reduced by using energy crop cultivations as buffer strips along open streams.

3.2.1. Reduced nutrient leaching in general

Growing perennial energy crops instead of annual food crops reduces the risk of water pollution through leaching and runoff, due to reduced input of fertiliser, longer growing season, soil cover all year round, and a more extensive root system [30, 31]. Nitrogen (N) leaching from short-rotation forest and ley production, for example, is estimated to be 30–50% and 75% lower, respectively, than from grain production [18, 32, 33]. This benefit will be greatest on coarse-textured sandy soils, as the nitrogen leakage from these soils is, on average, twice as high as from fine-textured clayey soils [33]. The average nitrogen leaching from arable land varies between 13 and 48 kg N/ha yr in southern and central Sweden, where the highest losses are for south-west Sweden [34].

It is assumed here that nitrogen leaching is reduced by, on average, 50% when perennial energy crops are used to replace annual crops, which is equivalent to about 10 kg N/ha yr [34]. This reduction can be achieved on about 60% of Swedish arable land (including both mineral and organic soils), on which annual crops are cultivated today.

3.2.2. Reduced nutrient leaching through buffer strips

Perennial energy crops could also be established between open streams and food crop cultivations as vegetation filters decreasing leaching and runoff [20, 35]. The efficiency of nutrient retention in these buffer strips depends on water flow pathways controlling the transport of nutrients through the landscape, and the composition and width of the riparian zones. Nitrogen retention by biological transformation, e.g., vegetation uptake and denitrification by micro-organisms, is increased by longer water transit times and is mainly confined to the upper soil stratum, thus affecting surface water and shallow groundwater [36].

If the field is tile drained, nitrogen retention in buffer strips will be significantly reduced since 80–90% of the nitrogen is transported in subsurface flows as dissolved nitrate (NO_3) [35]. The phosphorus (P) retention, on the other hand, is only affected to a small extent by tile drainage, as phosphorus transport mainly takes place as surface runoff, as more than 70% of the phosphorus is normally particle bound. Thus, the benefits of reduced phosphorus losses will be greatest on easily eroded soils, such as clayey and silty soils [37]. An increase in width of riparian zones up to 25 m will increase retention, where often more than 70% of the total content of nitrogen and phosphorus is removed from the water flow [35]. A prerequisite for a continuous high retention is, however, that the biomass is harvested regularly leading to an output of nutrients from the buffer strips, thus avoiding nutrient saturation.

It is assumed here that buffer strips, with a width of 50 m, consisting of energy crops, are established between annual crop cultivations and open streams. Half of the width (25 m) is harvested at a time, leading to a continuous high uptake of nutrients. The buffer strips consist mainly of *Salix*, but with a narrow zone of energy grass closest to the stream, for practical reasons. The nitrogen retention, which is assumed to be 2/3 by root uptake and 1/3 denitrification, is estimated to be, on average, 70 kg N/ha yr, when the nitrogen leaching from upstream cultivations of annual crops exceeds 15 kg N/ha yr [38]. There is only a small variation in the nitrogen retention in absolute terms, as a lower load of nutrient on the vegetation zone leads to higher relative retention, and vice versa. The phosphorus retention in buffer strips is estimated to be, on average, 1.5 kg P/ha yr [38]. The average loss of phosphorus from Swedish arable land is about 0.3 kg P/ha yr [39].

The occurrence of open streams in the farmland affects the possibility of establishing riparian buffer strips. Results from an investigation in southern Sweden show that the occurrence of open streams is about 6 m/ha, and the occurrence of streams in culverts about 7 m/ha [40]. Since there are no data for the rest of Sweden, an average value has been assumed in this paper. The occurrence of open streams in Swedish farmland has been estimated to be, on average, 8 m/ha. This is 30% higher than in southern Sweden, since this region consist of intensively cultivated clay soils with a high degree of tile drainage [10]. This assumption must be investigated further.

The theoretical maximum area of buffer strips (with a width of 50 m) for nitrogen retention, based on an occurrence of open streams of 8 m/ha in Swedish farmland, is equivalent to 2.6% of the current arable land. Arable land with tile drainage, ley production, and nitrogen leaching less than 15 kg N/ha yr, is excluded. Nitrogen leaching from 10–15% of current arable land could be treated in these buffer strips. The theoretical area of buffer strips for phosphorus retention on clayey and silty soils where annual crops are cultivated is equivalent to 3.7% of current arable land. Phosphorus leaching from 15–20% of Swedish arable land could be treated here. However, considering the practical application of perennial energy crop cultivations as riparian buffer strips, the potential area would probably be lower due to different obstacles not identified here.

The period of time during which energy crop cultivations will significantly reduce nutrient leaching is estimated to 25 years or more. Current measures in agriculture aiming to reduce nutrient leaching are not sufficient of attaining stated environmental goals [41]. Also, a structural change towards a more even geographic distribution of crop production and animal production takes time. According the National Swedish Environmental Protection Board [41], uneven geographic distribution of crop production and animal production is a major reason for the problems associated with nutrient leaching and eutrophication.

3.3. Heavy metals

The annual accumulation of cadmium (Cd) in Swedish arable soils is equivalent to 0.20–0.25% of the total content of cadmium in the soil, which has increased by around 33% during this century [42]. One result of this cadmium accumulation is that in southern Sweden, the cadmium content in grain harvested on intensively cultivated farmland sometimes exceeds the limit of 0.1 μg Cd/kg grain, proposed by WHO/FAO [43]. However, *Salix* plantations could be used to lower the content of heavy metals in arable land, as the uptake of heavy metals in *Salix* shoots is normally much higher than in other crops. The uptake of cadmium in *Salix* shoots, for example, is 35 to 70 times higher than in energy grass and straw [44]. The cadmium could then be removed from the ash through flue gas cleaning when the *Salix* is combusted [45]. There are, however, significant differences in the efficiency of cadmium uptake between different *Salix* species and clones [46–48].

It is mainly the fraction of cadmium in the soil available to the plant that is reduced by *Salix* [49, 50]. The plant-available fraction of cadmium in the topsoil normally amounts to 30–40% of the total cadmium content, depending on the pH and contents of clay and organic matter in the soil. The total content of cadmium in the topsoil of Swedish arable land has been estimated to be, on average, 600 g/ha [43]. The content of cadmium in *Salix* shoots varies between 0.4 and 3.9 mg/kg dry matter [49]. An average cadmium content of 2.0 mg/kg dry matter is equivalent to an uptake of about 20 g Cd/ha yr, when the annual increment in biomass is 10 tonne dry matter/ha yr. The annual uptake of cadmium will, however, decrease over time, as the fraction of plant-available cadmium in the soil is reduced. To some extent, cadmium might also be redistributed from the subsoil to the topsoil through deep *Salix* roots and litter fall, thus reducing the net output of cadmium from the top soil [49]. It is estimated that the highest output of cadmium from the topsoil through *Salix* cultivation could be achieved on soils with a high content of cadmium in the topsoil due to antrophogenic deposition, and with a low, natural, content in the subsoil [51].

It is here assumed that the annual net output of cadmium from the topsoil through *Salix* cultivation is equivalent to, on average, 1% of the current total content of cadmium. This output of about 6 g Cd/ha yr will exceed the yearly input of cadmium by 4 to 5 times. The period of time during which *Salix* plantations could significantly reduce the content of cadmium in the soil is estimated to be about 35 years, after which the plant-available fraction is assumed to be considerably reduced. The atmospheric deposition of cadmium, as well as the load from phosphorus fertilisers and sewage sludge, is assumed to be reduced in the future due to national environmental programmes in accordance with international agreements [52, 53].

3.4. Soil fertility and erosion

Current agriculture practices employing intensive soil tillage and a high proportion of annual crops, has resulted in loss of soil humus and decreased soil fertility [27]. Also, the impact on the Swedish agricultural landscape has been considerable, as both the number of fields as well as the occurrence of permanent vegetation zones have been drastically reduced since the 1930 s [54]. These changes have resulted in increased wind and water erosion [55, 56]. An increased proportion of perennial energy crop cultivations in the agricultural landscape may increase soil fertility and reduce soil erosion.

3.4.1. Increased soil fertility

An increased humus level in mineral soils by 0.5–1 percentage points after about 25 years of energy crop cultivation (see Section 3.1.1.), is estimated to increase food crop harvest by on average 5% [57]. This is valid for soils with a humus content of less than about 6%, as physical and chemical properties of the soil are improved up to this humus level [33]. Increased yields through higher levels of humus in mineral soils could then theoretically be achieved on about 47% of current Swedish arable land, considering mineral soils with a humus level of less than 6% on which annual crops are cultivated [10, 11]. The period of time during which higher yields of annual crops would be achieved is estimated to be equal to the period of time during which perennial energy crops were cultivated, for example, 25 years considering *Salix*. After that period, the humus level may decrease or be maintained, depending on future agriculture practices.

3.5. Decreased wind erosion

By using *Salix* plantations as windbreaks in areas exposed to wind erosion, higher yields in surrounding food crop cultivations could be achieved [58]. Wind erosion reduces crop yields through both direct damage, e.g., plant blasting, covered plants, and uncovered roots and seeds, as well as indirect damage from loss of organic matter and fine soil particles leading to reduced soil fertility [59]. Results from Swedish and Danish long-term field trials in areas exposed to wind erosion show a reduction in wind speed of 30–90% in fields with shelter belts less than 100 m apart [60–62]. Compared with fields which have shelter belts 150–350 m apart, the loss of clay and silt particles was 200–300 times lower and the humus level was about one percentage point higher.

It is assumed here that shelter belts with a width of 50 m consisting of *Salix* are established 100 m apart on fields exposed to wind erosion. One half of the width, or 25 m, is harvested at a time leading to a continuous high sheltering effect. The height of *Salix* in mature stands is about 5 m. The yields from intermediate annual crop cultivation is estimated to increase by, on average, 10% [58, 63]. There are, however, some uncertainties in this estimate as the shelter effect depends on the width of the shelter belts. The results of the Swedish and Danish field trials referred to above assume the width of the shelter belts to be less than 25 m. Thus, the estimate made here must be verified by practical field trials. The arable land exposed to wind erosion in Sweden, mainly sandy soils in southern Sweden, is estimated to have increased by 15% since the 1950 s, and now amounts to 40,000 ha [58, 64]. Thus, the theoretical area of *Salix* shelter belts will be 13,000 ha, equivalent to 0.5% of the total area of arable land.

3.5.1. Decreased water erosion

Perennial energy crop cultivation could also be used as vegetation zones preventing rill erosion, particularly on fields with clayey and silty soils in hilly areas. The degree of soil cover must be high, above 70%, to prevent water erosion [37]. Results from field trials with short-rotation forest show that the degree of soil cover in matured stands may vary from 5% up to 75%, and in newly harvested stands from 37% up to 100% [18]. Therefore, rill erosion and run-off could occur in *Salix* plantations with low soil cover [38]. Pimentel and Krummel [65] estimate, however, that soil erosion in short-rotation forests and in energy grass cultivations is, on average, 7 and 70 times lower, respectively, than in wheat cultivations.

Up to 20% of Swedish arable land is exposed to rill erosion. On about 5%, rill erosion causes soil losses of about 500 kg/ha yr, which sometimes leads to permanent land degradation [37]. In this paper, serious rill erosion is assumed to be prevented on 5% of arable land consisting of clayey and silty soils, by vegetation zones of energy crops (preferably energy grass). The vegetation zones, with a width of 50 m, are located 200 m apart on slopes, hollows, and other critical areas. Based on these assumptions, the theoretical area of vegetation zones preventing rill erosion is equivalent to about 1% of current arable land. The erosion, on an area equal to 0.5% of the field size, is assumed to cause permanent land degradation on every third occasion. Direct crop damage is assumed to occur on every second occasion, as rill erosion often occurs during winter on bare soil.

3.6. Municipal waste treatment

Energy crop cultivation is being tested in large-scale trials in Sweden as vegetation filters for municipal waste water, for example, in the municipalities of Svalöv and Bromölla [66]. Energy crop cultivations can also be utilised for the treatment of landfill leachate and sewage sludge. Interest in vegetation filters for municipal waste water treatment, as a complement to conventional treatment methods, has increased due to the problem of marine eutrophication [67]. Also, the cost efficiency of purification using vegetation filters is normally higher than for conventional treatment [68, 69]. Another benefit of waste water treatment in vegetation filters is that the amount of sewage sludge will be reduced [68, 70].

3.6.1. *Waste water treatment*

Around 75–95% of the nitrogen and phosphorus in the waste water could be removed in energy crop cultivations, when the waste water load is 500–1000 mm /ha yr [70–72]. An increase in waste water load to 2000–5000 mm/ha yr, will decrease the treatment efficiency to 10–55% [69, 73]. It has been estimated that a waste water load of about 600 mm/ha yr, containing 125 kg nitrogen, will not cause any long-term environmental problems such as nitrogen leaching [74]. This amount of waste water will supply, not only the demand for nitrogen and other macro-nutrients, but also the demand for water, which is often the limiting factor for growth. Nitrogen retention in vegetation filters is also, to some extent, caused by denitrification.

The nutrient content in municipal waste water matches the nutrient demand in energy crop cultivation quite well [71]. Waste water irrigation may increase the biomass yield by 2–3 times, compared with the case when no fertiliser is applied [75]. Compared with conventional fertilisation practices, the biomass yield is estimated to increase, on average, by 50% [76]. The nitrogen content in the waste water is reduced by 15–20% after a pre-treatment, which is needed for reducing the amount of solid particles. Thus, a waste water load of 600 mm/ha yr will supply around 100 kg nitrogen after a pre-treatment.

The combination of waste water treatment in vegetation filters during the summer months, and conventional phosphorus treatment during the winter months, has the highest cost efficiency, as the cost of storage ponds during the non-growing season is avoided [68]. Enhanced nitrogen removal will then occur only during the summer months, but it is during this season that the aquatic ecosystem is most vulnerable to eutrophication. With this combination of treatment systems, waste water from about 60 inhabitants may be treated on one hectare of energy crop cultivation. The amount of nitrogen in municipal waste water is, on average, equivalent to about 4 kg N/person yr [67].

The risk of accumulation of salts, heavy metals and other components in the soil from waste water irrigation is estimated to be small. The reasons for this are that the content of these components is normally low in municipal waste water, that precipitation in Sweden is much higher than evapotranspiration and that waste water irrigation is assumed to occur only during the summer period. In drier climates, however, there might be a risk of an accumulation of toxius, for example, salts from waste water irrigation.

The cost of waste water treatment in vegetation filters will increase with increasing size of the village or town, as longer pipes from the populated area to the vegetation filters will be needed. A rough estimation is that municipal waste water from about 70% of the Swedish population may be treated in vegetation filters at a lower cost than if only conventional treatment methods are used [6]. The area of energy crop cultivation required for waste water treatment will then be about 100,000 ha, which is equivalent to 3.6% of the total arable land [77]. The period of time during which vegetation filters will be useful as a complement to conventional treatment plants is assumed to be at least 25 years. This assumption is based on an estimate by the National Swedish Environmental Protection Board [67], bearing in mind that new treatment techniques which significantly reduce the amount of waste water, e.g., urine separation, composting/digestion of faeces, or reuse of grey water, will not be extensively implemented within the near future. This is mainly due to the low turnover of buildings, and technical difficulties in changing the sewage system in existing buildings.

3.6.2. *Landfill leachate treatment*

About 10 of the current 300 sanitary landfills in Sweden employ vegetation filters of *Salix* or grass for landfill leachate treatment [78]. Using on-site biological purification systems, instead of transporting the leachate to a conventional treatment plant, reduces the risk of contamination of the sewage sludge and leads to an increased possibility of recirculating the sludge on arable land [78]. Energy crops, such as *Salix* and reed canary grass, have high evapotranspiration which will reduce the amount of leachate. The amount of nitrogen in the leachate, which is normally the most problematic parameter from a pollution point of view concerning old landfills, can be reduced by 90% in vegetation filters [79, 80]. If the leachate contains high levels of heavy metals, these could also be reduced by using *Salix* (see Section 3.3.). The content of heavy metals in the leachate from Swedish landfills is, however, normally low [78]. There might be a risk of long-term salt accumulation in the soil as the content of, for example, chloride is normally much higher in landfill leachate than in municipal waste water. This risk has, however, not yet been analysed in field trials.

The average size of a vegetation filter for leachate treatment is about 3 hectares per landfill. The nitrogen content in leachate is, on average, about 150 g N/l [78]. Landfill leachate produced during the winter is stored in ponds. The theoretical area of energy crop cultivations as purification systems for landfill leachate will then be around 1000 ha, which is equivalent to about 0.04% of current arable land. If old sanitary landfills are also included, the amount of land required for vegetation filters will increase. The period of time during which vegetation filters will be needed for leachate treatment is as long as the anaerobic decomposition phase continues, or up to 100 years [78].

3.6.3. Recirculation of sewage sludge

The use of municipal sewage sludge as fertiliser in agriculture is a well established principle in Sweden. However, only about 35% of the sewage sludge produced is recycled, mainly on agriculture land, while 65% is deposited on landfills due to uncertainties in the amounts of heavy metals and toxic organic compounds in the sludge [81]. According to the National Swedish Environmental Protection Board [82], this sludge may be used in other cultivations than food crop cultivation, e.g., energy crop production, until the sludge quality is established.

Several studies have shown that using sewage sludge as nitrogen fertiliser in *Salix* cultivations leads to the same biomass yield as when commercial fertilisers are used, that the nutrient and metal leaching is insignificant, and that the content of heavy metals in the soil is almost unaffected [83–87]. Application of sewage sludge would also increase the humus level in the soil. Extremely high application levels (around 20 tonne dry matter/ha yr) could, however, cause nitrogen leaching and an increased content of cadmium in the soil [87].

The composition of nutrients in sewage sludge is, in contrast to municipal waste water, quite different from the plant demand, with an excess of phosphorus compared with nitrogen [71]. Thus, to ensure the optimum use of the nutrients in the sludge, complementary nitrogen fertilisation is required [74]. The maximum allowed application ratio of sewage sludge in Sweden is 5 tonne dry matter/ha every fifth year [82]. This application will fully supply the demand for phosphorus in energy crop production, and 20–30% of the demand for nitrogen [7, 87]. Sewage sludge could be applied to *Salix* cultivations after planting, or harvesting, using manure spreaders [88]. The theoretical area of energy crop cultivation that could be fertilised with municipal sewage sludge now being deposited at landfills is about 130,000 ha, or 4.8% of current arable land. The period of time during which a significant amount of sewage sludge may be used as fertiliser in energy crop cultivation, is here estimated to be 25 years or more. After that, the quality of the sewage sludge may have been improved through national environmental programmes, and thus be available for recycling in food production [67].

3.7. Biodiversity

Replacing annual crops by perennial energy crops will affect the biodiversity on a genetic, species, and habitat level. The diversity and occurrence of soil micro-organisms and soil fauna, especially decomposers such as earthworms, wood lice, harvest men, and carbides, is, in general, higher in energy forest and grass cultivations than in annual food crop cultivations [17, 18]. This is mainly due to the reduced soil tillage and use of agrochemicals, and to the increased input of litter. The average dose of chemical pesticides applied in *Salix* and reed canary grass cultivations is, for example, about 0.2 kg active ingredients/ha yr, while it is about 1 kg in annual food crop cultivation [7]. Cultivation of *Salix* (male plants) will also promote pollinating insects, such as bees and bumble-bees, as *Salix* flowers in early spring when the supply of pollen is limited [89]. About half of the *Salix* clones sold in Sweden today are male plants [90].

The composition of the ground flora in *Salix* cultivations, which depends on present management methods and earlier land use, is normally dominated by weed species, but rare species could also occur [91]. Results from an investigation in twelve *Salix* plantations in southern Sweden show an occurrence of 125 species of vascular plants, and 18 species of mosses [92]. In a grain cultivation, the frequency of weed species is around 50, of which about 30 occur only sporadically [93]. Energy crop cultivations may also improve the biodiversity indirectly in streams through reduced nutrient leaching [94].

Short-rotation forest will provide a transitional habitat promoting wildlife, specially in open farmland. Several studies show that both short-rotation forests and energy grass cultivations will increase the number of bird species, mainly song-birds, as well as the abundance of some species [95–97]. A proportion of 10 to 20% energy forest in open farmland has been estimated to be optimal for fauna, especially when the harvest is asynchronous in different sub-areas [96]. This will also improve the diversity of the ground flora [92]. Results regarding the effects of short-rotation forest on the occurrence of larger mammals, such as moose, deer, and hare, are not in agreement [33, 98]. However, considering a region including several different types of landscape, an increase in biodiversity in open farmland may not lead to an increase in the overall biodiversity in the region. Several of the birds and mammals occupying energy crop plantations are often widespread and regionally abundant in other landscape types [99].

Large-scale introduction of *Salix* may increase the risk of pests and diseases, such as rust fungus and herbivores. This is, however, not assumed to result in an increased use of chemical pesticides, as it is difficult, and thereby costly, to carry out chemical pest control in mature stands [100]. Alternative methods which can be used are, for example, breeding of resistant strains, biological pest control of herbivores, and a more diverse clonal composition which also leads to increased yields [101–103]. Another risk associated with large-scale introduction of *Salix* cultivation is genetic contamination of surrounding wild native *Salix* species through hybridisation with foreign species [33, 103]. One solution to this problem could be the development of sterile clones [20]. Today, mainly native species of *Salix* are used in Sweden [90].

In this paper, it is estimated that the overall biodiversity in a larger region is not, or only to a small extent, affected by a substitution of annual crops by perennial energy crops. If any change occurs, the biodiversity will probably increase, mainly in open farmland. A similar conclusion has been drawn by the National Swedish Environmental Protection Board [91].

4. Conclusions and discussion

An overall conclusion of this study is that the environmental benefits from large-scale introduction of energy crop production in Sweden could be substantial, as the negative environmental impact from current agriculture practices and municipal waste treatment could be significantly reduced. The carbon dioxide emission from organic soils through biological oxidation of the organic matter, for example, could be significantly reduced (by about 7 tonne C/ha yr) when annual crops are replaced by perennial energy crops (Table 2). The greenhouse gas mitigation from changed land use on mineral soils, through soil carbon accumulation and reduced nitrous oxide emission, is around 1/10 and 1/100, respectively, of that through changed land use on organic soils. As a comparison, the reduction of carbon dioxide emissions due to the lower input of fossil

Table 2
Summary of environmental changes, including the recirculation and treatment of municipal waste, when perennial energy crops replace annual food crops, the maximum area of energy crop cultivation where a change occurs expressed as per cent of the total Swedish arable land, and the period of time during which the change is estimated to last. When the energy crop cultivations affect surrounding cultivations of food crops, this area is given within parentheses, expressed as per cent of the total Swedish arable land

Changed environmental impact	Average quantitative impact *	Maximum proportion of total arable land (%)	Period of time (years)
Accumulation of soil C in mineral soils	0.5 tonne C/ha yr	55	~50
Reduced CO_2 emission from organic soils	7 tonne C/ha yr	5.0	~80
Reduced N_2O emission from mineral soils	0.04 tonne C-equivalents/ha yr	55	∞
Reduced N leaching in general	10 kg N/ha yr	60	> 25
Reduced N leaching through buffer strips	70 kg N/ha yr	2.6 (10–15)	> 25
Reduced P leaching through buffer strips	1.5 kg P/ha yr	3.7 (15–20)	> 25
Cadmium removal	6 g Cd/ha yr	92	~35
Increased soil fertility	5% higher yield	47	> 25
Reduced wind erosion	10% higher yield	0.5 (1.5)	∞
Reduced water erosion	Reduced land degradation and plant damage on 0.5% of the field area	1.0 (5.0)	∞
Waste water treatment	100 kg N/ha yr		> 25
(sparsely populated areas)		2.5	
(populated areas)		0.7	
(densily populated areas)		0.4	
Landfill leachate treatment	100 kg N/ha yr	0.04	~100
Recirculation of sewage sludge	1 tonne dry matter/ha yr	4.8	> 25
Biodiversity	Unchanged/increased in open farmland	60	∞

* The average quantitative impact presented should be seen as average estimates which could vary significantly due, among other things, to local conditions. A more integrating sensitivity analysis is presented in Part II of the analysis, in the second paper (see Börjesson [6])

fuels for the production of perennial energy crops production than of annual food crops, has been estimated to amount to about 0.2 tonne C/ha yr [8]. When the biomass is used to replace fossil coal in heat and power production, the carbon dioxide mitigation amounts to 5–6 tonne C/ha yr, thus the reduced carbon dioxide emissions from changed use of land on organic soils could exceed this mitigation [104].

If perennial energy crops are cultivated on 30% of the total Swedish arable land, this could lead to a reduction in the total emissions of greenhouse gases from agriculture by 15–25%, based on the results presented in this paper [105]. Today, the contribution of greenhouse gases from agriculture, mainly consisting of carbon dioxide emission from drained and cultivated organic soils, amounts to 15% of the total Swedish emissions [105]. The Biomass Commission of the Swedish Government [9] has estimated the amount of arable land not needed for food production for domestic consumption, and thus available for energy crop production, to about 800,000 ha around 2005 (equivalent to about 30% of the total Swedish arable land). The reduced carbon dioxide emission from organic soils is, however, caused by the cessation of annual crop cultivation leading to less frequent soil tillage, and not particularly by the cultivation of perennial energy crops. Thus, an equivalent reduction of carbon dioxide emission is assumed to be achieved when the land lies fallow, as when perennial crops are grown. Also, the reduced nitrous oxide emission from mineral soils is caused by the reduced input of nitrogen fertilisers, and not particularly by the cultivation of energy crops.

The greatest reduction in nitrogen emission to surface and ground water is achieved when energy crop cultivations are used as vegetation filters for waste water treatment. A somewhat lower reduction is achieved when energy crop cultivations are used as riparian buffer strips, followed by recirculation of sewage sludge, and replacement of annual crops. When energy crop cultivations are utilised as riparian buffer strips, where possible, nutrient leaching from Swedish agriculture could be reduced by 15–25% [106]. Nutrient leaching from arable land amounts to, on average, 30% and 10% of the total Swedish nitrogen and phosphorus loads to water [106]. In intensively cultivated agricultural areas, however, the nutrient leaching could be much higher, up to 75% [107, 108]. Through the extensive use of energy crop cultivations for municipal waste water treatment, as a complement to conventional treatment methods, the discharge of nitrogen to water, and the generation of sewage sludge, may be reduced by 40%, compared with current treatment technology in Sweden [109]. Also, nitrogen equivalent to about 6% of the current use of commercial fertiliser in Sweden could be reused [10, 81]. When sewage sludge now being deposited on land fills is recirculated on energy crop cultivations, nitrogen and phosphorus equivalent to about 2% and 20%, respectively, of the current use of commercial fertiliser in Sweden, could be reused [10, 81].

The yield increase in surrounding food crop cultivations is greatest when *Salix* is used as shelter belts preventing wind erosion, followed by energy crop cultivations as vegetation zones preventing water erosion.

The environmental benefits identified in this paper could be achieved on large areas of arable land, up to 60% of the land on which annual crops are cultivated today. The occurrence of open streams limits the use of energy crop cultivations as buffer strips, while the amount of municipal waste limits the use of energy crop cultivations as vegetation filters.

The environmental advantages could last for a long period, 25 years or more. Reduced wind and water erosion will last as long as energy crops are cultivated. How long soil carbon accumulation and cadmium removal will last, depends on the physical and chemical properties of the soil, while the thickness of the peat layer determines how long the reduction in carbon dioxide emissions from organic soils will last. The carbon dioxide mitigation through changed land use where energy crops have replaced food crops, will be gradually reduced and then cease. However, this carbon dioxide mitigation will be achieved again on new cultivation sites when energy crop cultivations are moved. The possibility of the future use of energy crop cultivations to reduce nutrient leaching and to treat municipal waste, depends on the development of agricultural practices, the load of pollutants, and the production of waste.

There are several uncertainties in the estimates presented in this paper, e.g., concerning carbon dioxide emission from organic soils, accumulation of soil carbon in mineral soils, nitrous oxide emission, nutrient removal in buffer strips, cadmium removal, and wind and water erosion. The emission of nitrous oxide, for example, may vary greatly depending on soil type, type of fertiliser used, climate and land management practices. Thus, local conditions will affect the magnitude of the reduction of nitrous oxide emissions when energy crops replace annual food crops. Concerning the magnitude in the reduction of carbon dioxide emissions from organic soils due to the change in land use and the accumulation of soil carbon in mineral soils, these theoretical calculations have not been verified by field trials. The nutrient removal in buffer strips and the occurrence of water erosion also depends on local conditions, thus, the variation could be significant due to, for example, soil type and how hilly the landscape is. How efficiently 25–50 m-wide shelter belts of *Salix* will reduce wind erosion, in comparison to 5–10 m-wide, must also to be analysed in field trials. The magnitude of cadmium removal could vary greatly, depending on both soil conditions, such as pH and content of clay and organic matter, and the efficiency of the cadmium uptake concerning the specific *Salix* clone.

Another uncertainty concerns the benefit of the decreased use of chemical pesticides in the cultivation of perennial energy crops as compared to annual food crop cultivation. As described in Section 2, no data have been found of, for example, the risk of water pollution by pesticides used in perennial energy crop cultivation, in comparison with annual food crop cultivation. However, such a risk should be lower, as the average dose of chemical pesticides applied in annual food crop cultivation is about five times higher than in *Salix* and reed canary grass cultivations (see Section 3.6.) Thus, the benefit of a reduced use of chemical pesticides is probably underestimated in this analysis, as it is included only in the impact on the biodiversity.

Concerning other environmental impacts identified in this paper, such as waste water and landfill leachate treatment, and recirculation of sewage sludge, the uncertainties in the calculations are estimated to be lower. Thus, considering the magnitude of the different environmental changes presented in Table 2, these should be seen as average estimates which could vary significantly due, among other things, to local conditions. A more integrating sensitivity analysis of the various environmental changes is presented in Part II of the analysis, in the second paper (see Börjesson [6]).

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