

Biofuel plantations and isoprene emissions in Svea and Götaland

Zahra Khais Shahid

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Department of
Physical Geography and Ecosystem Science
Centre for Geographical Information Systems
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden



Advisor: Thomas Holst
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Supervisor: Thomas Holst
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Abstract

Bioenergy as an alternative source for energy production and transportation has gained attention to mitigate greenhouse gas emissions from fossil fuels. Short Rotation Coppice (SRC) as dedicated energy crops for heat and energy production have many demonstrated and proved climatic, biodiversity and environmental benefits, but concerns regarding the occurred Land Cover Change (LCC) from agriculture land into SRC have been raised. Since they are recognized as high isoprene emitters at higher rates than other croplands and once isoprene interact with Nitrogen dioxide (NO_2) it would lead to O_3 formation to unhealthy levels. A Geographical Information System (GIS) model used in this study offered a simple method to quantify LCC. Different geoprocessing tools and zonal (Spatial Analyst) tools such as tabulate area to explore the distribution of biofuels plantation areas, SRC and rapeseeds, are relative to each land cover type. And to calculate the increases in isoprene annual turnovers caused by cultivation of thousands of hectares of SRC in Svealand and Götaland regions, a simplified methodology for isoprene annual emissions has been used. The GIS model was used to generate maps and GIS analyses and then relate isoprene emissions with SRC plantations and other ecosystem types. The results showed that the temporal development of the areas used for willow and rapeseed plantations increased between the time period 2002 and 2008 and declined between 2008 and 2014, except for poplar which showed a rise in the covered area from 2002 to 2014. Also, an increase in the number of small plots that are equal or less than 6 ha and removing large plots was obvious during that period, and the areas used for rapeseed were larger than the areas used for SRC. LCC was basically from non-irrigated arable land into SRC and rapeseed crops, about 95% of LCC from non-irrigated arable land into energy crops was dedicated to rapeseed and only 5% of LCC was dedicated to SRC in 2014, this pattern has not changed since 2002. The emitted isoprene from SRC due to LCC was almost 9 times more than the emitted isoprene from the corresponding area of other agricultural crops. The results would support the decision making process about the selection of SRC locations in the context of LCC from agriculture land and other land cover types, and in the context of the anthropogenic pollutants NO_2 to avoid or reduce the effects of LCC into SRC on air quality in Sweden.

Keywords

Geographical Information Systems (GIS), Short Rotation Coppice (SRC), Isoprene, Nitrogen dioxide (NO_2), Biofuels.

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Abbreviations List

| | |
|-------------------------|---|
| C_T | Correction factor for temperature |
| H_2O_2 | Hydrogen peroxide |
| N_2 | Nitrogen |
| ND_{mm} | Number of days per month |
| NL_{mm} | Number of light-hours per day |
| O_2 | Singlet oxygen |
| O_{2-} | Superoxide |
| O_3 | Ozone |
| T_{mm} | Monthly mean temperature |
| C_L | Correction factor for light |
| $^{\circ}C$ | Celsius degree |
| $\mu g\ m^{-2}h^{-1}$ | Micrograms per square meter per hour |
| $\mu mol\ m^{-2}s^{-1}$ | Micromoles per Square meter per second |
| | |
| BUM | Background Urban Model |
| BVOC | Biogenic Volatile Organic Compounds |
| | |
| CO_2 | Carbon dioxide |
| CHP | Combined heat and power |
| CIESIN | Center for International Earth Science Information Network |
| CLC | Corine Land Cover |
| CO | Carbon monoxide |
| D | Foliar density |
| EMEP | European Monitoring and Evaluation Program |
| EMEP MSC-W | EMEP Meteorological Synthesizing Centre-West |

| | |
|---------------|---|
| ESRI | Environmental Systems Research Institute |
| EU | European Union |
| EUR | Euro |
| FAME | Fatty Acid Methyl Esters |
| FAO | Food and Agriculture Organization |
| GHG | Greenhouse gases |
| GIS | Geographical Information System |
| GJ | Gigajoules |
| GWh | Gigawatt-hour |
| H | Hydrogen |
| Ha | Hectares |
| HVO | Hydrogenerated Vegetable Oil |
| Hydrocarboxyl | HOCO |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| IspS | Isoprene synthase |
| K | Potassium |
| Kg | Kilogram |
| kr/l | Kronor per liter |
| Kwh | Kilowatt-hour |
| LAI | Leaf area index |
| LCC | Land Cover Change |
| LUC | Land Use Change |
| MATCH | Multi-scale Atmospheric Transport and Chemistry |
| MCMv3 | master chemical mechanism |
| MEGAN | Model of Emissions of Gases and Aerosols from Nature |
| Mha | Million Hectare |

| | |
|---------------------|--|
| µg/m ³ | Micrograms per cubic meter |
| MJ/ kgdm | Megajoule per kilogram dry matter |
| mm | Month |
| MWh | Megawatt -hour |
| NO ₂ | Nitrogen dioxide |
| NO | Nitric oxide |
| n.d | No Date |
| O | Oxygen |
| odt | Oven dry ton |
| OH | Hydroxyl radical |
| OH ⁻ | Hydroxyl radicals |
| P | phosphorus |
| PM ₁₀ | Particulate matter |
| pH | Potential hydrogen |
| ppb | Parts per billion |
| ppbc | Parts per billion CARBON |
| PPFD | photosynthetic photon flux density |
| REA | relaxed eddy accumulation |
| ROS | Reactive oxygen species |
| <i>S. viminalis</i> | <i>Salix.viminalis</i> |
| SEK | Swedish Krona |
| SIMAIR | Simulation Air |
| SLA | Specific leaf area |
| SMHI | Swedish Meteorological and Hydrological Institute |
| SRC | Short Rotation Coppice |
| tdm/ha | Ton dry matter per hectare |
| Tgyr ⁻¹ | Teragram per year |
| TWh | Terawatt-hour |
| VOC | Volatile Organic Compounds |

| | |
|----------|--|
| WHO | World Health Organization |
| WRF/Chem | Weather Research and Forecasting with Chemistry |
| Yr | Year |
| Γ | Integrated value |

Chapter 1 Introduction

1. Introduction to biofuels

Bioenergy as an alternative source of energy production and transportation has gained attention all over Europe for political reasons because of the increased greenhouse gas emissions from fossil fuels. The European target set by 2020 is to generate 20% of the total energy supply from renewable energy sources (EC, 2014) and bioenergy is one of the main resources that will be considered to meet this objective (Sixto et al., 2011). Yet, it is likely that would involve land cover change (LCC) on large scale to produce the required biomass which eventually could affect air quality in terms of increased O₃ formation (Hardacre et al., 2102). The most popular biofuel crops are; food crops such as sugarcane, corn, rapeseeds, and palm oil, which are featured as first generation biofuels and mostly used in the transport sector in the form of liquid or gas (Sims et al., 2008). And dedicated energy crops known as second generation biofuels, mostly used for energy generation purposes such heat and electricity; these crops are such reed canary grass, miscanthus, willow and poplar which are known as Short Rotation Coppice (SRC) (Sims et al., 2008). SRC are used as solid biomass fuels in energy production sector in small industries, but mostly in combined heat and power plants (CHP) and as pulpwood. They are very popular type of biomass since they grow so fast and photosynthesize in higher rates (Vitousek, 1991) such as poplars, and considered cost efficient in terms of production processes (Karp and Shield, 2008). For instance, the potential yield of fertilized willow plantations could have yield range between 10 and 25 ton per ha (Heinsoo & Koppel, 2002). Willow (*S. viminalis*) is one of the most dominating commercial willow species in Sweden, and they were originally introduced in the 1700's from continental Europe for basket making purposes (Verwijst et al., 2013). It is often bred with other willow species such as *S. schwerinii*, *S. dasyclados*, *S. aegyptiaca* and *S. triandra* to produce different willow varieties. Currently there are about 10 willow varieties under the breeding program managed by Lantmännen Lantbruk. (Albertsson, 2012) The breeding process used in the production system also contributes to increase plantations' resistance to diseases (Åhman & Larsson, 1994).

The SRC life cycle as described in the Abrahamson et al. (2010) handbook has to start with a site preparation any time in July on a suitable land with a proper soil type for SRC and go through weed control program. The following spring, land must be lightly disked and then the planting season starts in April or May with a specific planting design that needs to be followed. The SRC cuttings are supposed to produce roots and shoots after 2 weeks. Once they are established, they will be able to produce for the next 20 years, then an immediate weed control

program is followed. In the first growing season, ideally shoots would be 3 feet tall, in November or any time before spring plants is coppiced. From a second to the fourth growing season, fertilizers will be added during spring just after coppicing plantations, where plants should be 6-8 feet tall with a number of stems. When they are 3 years old (4 growing seasons) they are ready to be harvested during winter using harvesting machines that chops the stems and blows them into a wagon pulled in the back of the tractor, harvesting are repeated every spring for a 4 year cycle (Abrahamson et al., 2010). And that's about 7 to 8 total harvests before replanting which each requiring a 3- 4 year rotation period (U.S. Department of Energy, 2011) with a first harvest is carried out in the fourth year. Willow biomass yield in the north-eastern part of Sweden range between 8-9odt (oven dry ton substance) per hectare (ha) per year, eastern part between 9-10odt/ha/yr and in the southern and south-western is between 11-17odt/ha/yr (Lindroth and Båth, 1999), and an estimated yield productivity of 41 poplar stands was about 70–105odt/ha/yr (Johansson and Karačić, 2011). Also, an investigation has been conducted by the Forestry Institute of Sweden and the Swedish University of Agricultural Sciences (Rytter et al., 2011) to find out the potential of poplar productivity, which showed that poplar could be a huge biomass contributor in the energy sector once the suitable cultivation and breeding methods are used along with the positive social attitudes towards intensive cultivation. In order to meet the European objective set in 2020; SRC yield need to be close to or at least 27 million tons per year to produce 93 terawatt-hour (TWh) of energy by 2020 (Kuiper, Sikkema, and Stolp, 1998), which means a total of 8 million ha of agricultural land is needed for SRC cultivation in Europe (Mola-Yudego and Pelkonen, 2008).

Willow and poplar are cultivated on agricultural land but the Swedish forest agency has categorized SRC biofuel as part of wood biofuels products which are mainly used for heating and electricity production (Skogsstatistisk årsbok, 2014):

1. Forest fuel (skogsbränsle): branches, tree tops, stumps and by-products (bark, chips and sawdust), wood that has not been used before;
2. Recycled wood fuel (återvunnet träbränsle): wood from demolition projects and packaging, wood that has been used before;
3. Short rotation-forest fuel or Energy forest fuel (energiskogs bränsle): tree species that were dedicated to energy production such as willow and poplar, wood that has not been used before.

The turning point in the Swedish government policies regarding the use of biofuel was after the decision to shut down nuclear power plants (Barsebäck 1 and 2) in 1996 and the search for other energy sources was urgent. Therefore, encouraging establishment of SRC plantations among farmers was one of the measures that have been taken during the 1990's. These measures translated into actions such as; subsidies to farmers who transfer their croplands from cereal to willow plantations (Johansson et al., 2002); increased taxes on CO₂ levels from 0.37 SEK/kg in

2000 to 1.12 SEK /1kg in 2015 (Rolf et al., 2017) and establishment of good district heating systems infrastructure (Johansson et al., 2002).

In 2013, the total energy use in Sweden was about 406TWh and the supply from bioenergy was the largest of about 130.2TWh (Hektor, Bruce, and Andersson, 2014) i.e. 33.6% of the final energy use in the industry, heat, electricity and transport sectors came from bioenergy while other renewable energy sources such as hydro and wind power formed 16.4% of the total energy use in the country. Forest fuel was the largest contributor (Hektor, Bruce, and Andersson, 2014) generating 92TWh of heat and power and forms about 85% of the total biofuels supply. Bioelectricity from CHPs has about 9% share of the total generated electricity in Sweden, and about 6.5TWh of bioelectricity generated in district heating was based on wood fuels, peat and waste. This trend of increasing energy production based on biofuels is expected to continue in the coming years. In addition to district heating, the forest industry companies have interests in bioelectricity production, particularly after the introduction of incentives in the form of the electricity certificate trading scheme. About 40 plants produce bioelectricity where the largest plant has the capacity to generate 6TWh every year (Andersson, 2012).

All of that interest and attention from industries and governments in biofuels raised concerns related to LCC when it comes to converting agriculture food crops into energy crops on agricultural land (Fargione et al., 2008) even though the land changes could be indirect. Concerns regarding the occurred LCC are related to the Biogenic Volatile Organic Compounds (BVOC) emitted from SRC and hence air quality issues are elevated. There are number of studies that demonstrated the impacts of willow and poplar on air quality, which are recognized as high BVOCs emitters release organic compound of isoprene (Copeland, Cape, and Heal, 2012) in large amounts. Thus, LCC to bioenergy crops (Ashworth, Wild, and Hewitt, 2013) could have effects air quality but that is highly dependent on nitrogen dioxide (NO_2). Isoprene involvement in air quality degradation comes from its interaction with NO_2 and thus producing tropospheric Ozone (O_3). A chemical interaction between BVOC and high concentrations of NO_2 under high temperature and sunlight (Guenther et al., 1993) leads to enhancing O_3 levels (Ashworth, Wild, and Hewitt, 2013) and particles (Kiendler-Scharr et al., 2009) thus affecting air quality regionally and globally.

Chapter 2 Literature Review

2.1 Short Rotation Coppices

SRC have many demonstrated and proved climate, biodiversity and environmental benefits. The phytoremediation cleanup technique is one important method to mitigate environmental issues by using willow and poplar to clean up the soil since they have the capacity to absorb heavy metals from agriculture land (Lewandowski et al., 2006). This method is excessively used in Sweden to applying sludge or waste water that contains nutrients in willow cultivation and decrease the use of fertilizers (Mirck et al., 2005). The environmental advantages come with regard of fungicides and insecticides absence in the production process of SRC except the addition of herbicides during the establishment stage (Gustafsson, Larsson, and Nordh, 2007). In addition to the fact that other biofuel crops such as rapeseed would need more fertilizers than SRC, hence it is more cost efficient in terms of production process cost than other biofuel plantations (Feehan & Petersen, 2003).

The biodiversity benefits derived from SRC plantations have been shown to be more beneficial than rapeseed crops (Anderson et al., 2003). During the establishment of SRC plantations, a weed control program is important for young vegetation as it is mentioned above, when they are short and sparse vegetation, then it is when most suitable for seed eating passerines birds (Anderson et al., 2003). Additionally, the diversity of insects in willow plantations may provide food resources for insects during flowering periods (Reddersen, 2001). A comparative study between poplar plots and arable fields has shown that floristic diversity was increased on poplar landscape by providing a diversity of habitat that are shade tolerant compared to arable fields (Karačić, 2005).

A case study (Hammar, 2015) in south-eastern Sweden which evaluates the climate benefits between two types of biomass willow and logging residues which both are used in CHP plants has shown that growing willow on a set-aside arable land has sequestered carbon from the atmosphere into the soil, however that depends highly on willow productivity. Also, willow combustion has shown to have lower climate issues than coal and natural gas. On the other hand, logging residues have shown to have less climatic issues compared to coal due to its chemical combustion but not as much as willow plantations.

With respect to released emissions from SRC, several studies have shown that isoprene acts as a protective mechanism against stress conditions such as O₃ and high temperature to protect SRC

plantations, specifically, poplar plantations which have antioxidative properties and isoprene make plants tolerate O_3 (Sharkey, Wiberley, and Donohue, 2008). Isoprene acts as an antioxidant within leaves and a shield against reactive oxygen species (ROS) that comprised by singlet oxygen (O_2), superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH^-) caused by abiotic stress (Vickers et al., 2009). This protective mechanism against abiotic stress damage tends to be better worked in isoprene emitted species with respect to their abundance because of their resistance to O_3 damage than for non-isoprene emitted plantations (Lerdau, 2007). On the other hand, isoprene emitted plantations causes more damage to non-isoprene plantations. For instance, oaks and palms would benefit from this mechanism over other forest groups in temperate and tropical systems and in the end that would alter forest ecosystems in addition to their contribution to higher O_3 levels in high NO_2 levels (Lerdau, 2007).

2.2 Isoprene and NO_2 impacts on air quality

Biogenic VOCs are composed of different molecules; carbon, hydrogen and oxygen atoms, main compounds are isoprene (C_5H_8), monoterpenes ($C_{10}H_{16}$), as the amount of carbon might exceed 1000 Tg (Teragram) annually and about 90% of emitted BVOCs come from vegetation (Guenther et al., 1995). The largest source of isoprene is emitted by terrestrial vegetation (Guenther et al., 2006). It is a reactive compound which leads to changes in air chemistry and emergence of O_3 (Chameides et al., 1988). For example, methane (CH_4) life time could be increased by 15% due to the chemical reaction with BVOC in the atmosphere (Poisson et al., 2000) which leads to global warming and SRC isoprene emitters are major contributor to increased O_3 regionally and globally (Ashworth et al., 2012).

The impacts of BVOC emissions on air quality are measured by the magnitude of O_3 and aerosol formation in the atmosphere which potentially has impacts on global climate (Constable et al., 1999) and is considered very dangerous to human health (Claeys et al., 2004) and in some cases this can be corresponded to the same carbon quantities that are emitted from fossil fuel and biomass combustion (Lioussé et al., 1996). On the other hand, there is evidence that isoprene has a secondary potential impact on global warming with respect to indirect radiative forcing and that has to be legislate to combat climate change (Collins et al., 2002), there is about 3500 kiloton of isoprene was emitted in Europe between 2004 -2005 (Karl et al., 2009). Isoprene emission rates from SRC are ten times more than arable land and two to six times more than deciduous forest (Simpson et al., 1999b). Willow and poplar considered the strongest isoprene emitting plantations (Guidolotti, Calfapietra, and Loreto, 2011) and they also emit small amounts of monoterpenes (Hakola, Rinne, and Laurila, 1998) produced from isoprene synthase (IspS) and monoterpenes synthesis (TPS), which are both extremely active under 40-45°C temperature

degrees (Staudt & Lhoutellier, 2011) coupled with high a photosynthetic photon flux density (PPFD).

In addition to formation of O₃, PM₁₀ would also be a potential formation due to the chemical reaction between isoprene and NO₂ (Lin et al., 2013). PM₁₀ sources can be anthropogenic or natural, but in both cases, they affect human health and plants. According to a study conducted in the European Union (EU), every increase of 10µg/m₃ in PM₁₀ contribute to increase lung cancer rate +22% since they can penetrate unfiltered into lungs (Raaschou-Nielsen et al., 2013). BVOCs are one of the main efficient sources to form O₃ in the air once it reacts with NO₂ which is emitted from anthropogenic sources. The production of O₃ starts with a photolysis of NO₂ into NO (equation 1). The oxygen atom (O) reacts with a molecule O₂ to form O₃ and the presence of N₂ or O₂ would absorb the energy from the reaction between O and O₂, and then the formation of O₃ is completed (equation 2). O₃ is destroyed once it reacts with NO to again form NO₂ and gets back to O₂ (equation 3). These reactions are very fast and take only few minutes which provide a steady state O₃ background level (Crutzen, 1979). A disruption of this steady state process occurs once hydrocarbons in VOCs are introduced into the system. When Hydroxyl radical (OH) reacts with a carbon monoxide (CO) it produces a radical intermediate (HOCO), then forming carbon dioxide (CO₂) and hydrogen (H) (equation 4). This is followed by a reaction with O₂ in the presence of N₂ molecule to produce the hydroperoxyl radical (HO₂) (equation 5).

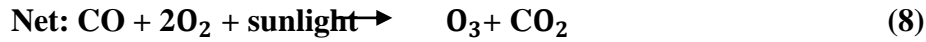
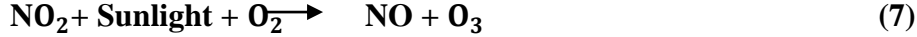
The biogenic VOCs will replace O₃ in the conversion process of NO to NO₂, and here VOC are composed of hydrogen and oxygen atoms (HO₂) (equation 6), and the O₃ will continuously be formed and cannot be destroyed by photolysis of NO₂ (equation 7). The O₃ production is sunlight, N O₂ and biogenic VOCs dependent so it varies from one location to another (Chameides, 1992). The following are chemical reactions to produce O₃ in the absence and presence of biogenic VOCs (Ryan, 2002):

Production and destruction of O₃ cycle in clean environment, in the absence of VOC; N₂ stabilizes the formed O₃ molecule



Production of O₃ cycle in a polluted environment in the presence of VOCs





In equation 8, the net effect continues as long as there are hydrogen and oxygen bonds and that lead to create many O₃ molecules from one isoprene molecule when NO_x levels are high (Sharkey, Wiberley and Donohue, 2008). However, the reaction could be different in very low NO₂ levels area and isoprene could reduce O₃ in the atmosphere according to Trainer et al., (1987). The reaction of isoprene in low levels of NO₂ in forest region leads to less than 2–3 parts per billion (ppb) per hour. Whereas 6–8 ppb per hour was released in high levels of NO₂ area (Geng et al., 2011). The O₃ levels is also changing according to the mixture of VOC and NO₂ i.e. the rate of VOC divided by NO₂, at 1,000 ppbC of VOC and 100 ppb of NO₂, the O₃ change from 300 to 280 ppb. And at 500 ppbC VOCs and 100 ppb NO₂, O₃ reduction is even more from 160 to 120 ppb and that is because of the reactivity of aldehydes in generating short-lived free radicals (National Research Council, 1991).

2.3 Impacts of willow and poplar LCC on air quality

Different studies carried out in recent years have focused on the negative impacts of LCC into biofuel crops on air quality in terms of increased O₃ in the ambient air. An evaluation of biofuel crops impacts on air quality and how LCC from Non-BVOC plantations into BVOC emitters contributed to O₃ formation in USA carried out by Porter (2013). In that study a high-resolution regional chemical transport model WRF/Chem (Weather Research and Forecasting with Chemistry) to quantify the impacts had been used. NO_x emissions were generated by National Emissions Inventory dataset (NEI05) and the BVOC emissions generated by the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.0.

The study confirmed that both Eucalyptus and giant reed have had climatic and health costs up to about 40% of the reduced CO₂ emissions whereas Switchgrass showed almost no impacts on air quality regardless of their spatial locations. Large scale conversion of grassland and agriculture land into high emitting crops have shown negative impacts on air quality in high NO₂ background and even in low NO₂ level areas.

Another study which has used a probabilistic method determined the impacts of LCC on air quality in 2015 and predicted them in 2030 (Hardacre et al., 2012). The study was directed by Intergovernmental Panel on Climate Change (IPCC) AR4/SRES scenarios A1 and B1 to ensemble future LCC using the Parsimonious Land Use Model (PLUM). Two of the IPCC assumptions have been used; no change in policy; and keep CO₂ levels lower than 450ppm. MEGAN has been used to generate changes in BVOC emissions using different input parameters

and LCC has been generated from PLUM and the biofuel assumptions. Also, GEOS-Chem global 3-D chemistry transport model was used to quantify the changes in O_3 in 2015 and 2030. The results of their future projection in 2030 indicated that the changes in land cover could lead to increased isoprene emissions from 2.8 Tgyr⁻¹ in 2015 to about 6.4Tg yr⁻¹ in 2030, and a monthly rise in O_3 levels between 0.1 and 0.8 ppb in sub-continental regions estimated from changes in isoprene and NO_2 emissions. The model also showed that O_3 increased between 5 and 12 ppb because of increased isoprene emission from SRC plantations over temperate North America, China and boreal Eurasia. Globally there were no major effects of LCC on O_3 surface, but larger on the local scale.

Ashworth et al. (2012) focused on isoprene emissions from SRC and oil palm and investigate the effects of LCC on air quality in terms of increased O_3 levels in the ambient air. The model used was the 'UK Met Office Hadley Centre's Earth system model' (HadGEM2) and anthropogenic emission and LCC had been used as input parameters to give an insight to vegetation distribution with and without biofuel crops. A comparison between two scenarios were based on future governmental policies showing potential oil palm and SRC locations in the 2020s and the native species on the other hand, to investigate the impact of LCC from agricultural land into SRC. In total about 92 million ha (Mha) of SRC are planted around the world which has increased global isoprene by 1% and regionally by 16% i.e. from 23 to 26 Tgyr⁻¹. The results also indicate significant changes in O_3 levels that affected air quality standards, as monthly mean increases by 0.6 ppbv.

Other study aimed to measure isoprene flux from willow (*S. viminalis*) in western Sweden (Olofsson et al., 2005), specifically in vicinity to urban areas. It used a relaxed eddy accumulation (REA) technique to measure isoprene emissions from willow. Then, the chemistry of air parcel was modeled using the master chemical mechanism (MCMv3) and a Lagrangian box model over the willow field. The study confirmed that isoprene flux had no major impacts on the local air quality since the dispersion process was faster than the chemical reactions with NO_2 in order to form O_3 . Although, this is subject to change once the atmospheric mixing is restrained under a stratified surface layer, therefore, it is recommended to plant willow in areas where the atmospheric mixing is not restrained by topography.

Many of the above mentioned contemporary researches have focused on climatic issues that arise from LCC into SRC and other biofuel crops, and highlighted the environmental and biodiversity benefits of SRC plantations for biofuel. Apparently, different methodologies were used to estimate isoprene emissions from SRC and modeling air sensitivity using chemical transport model. All of them are motivated by the fact that isoprene fluxes contribute in O_3 production in a high NO_2 atmospheric background lead to human health problems. The contribution of this thesis is that no quantification of LCC from forest or agriculture land into SRC plantations neither annual isoprene emissions released from SRC and other land uses have been carried out in Svealand and Götaland regions. In this study a GIS analysis and simpler methodology

(Simpson et al., 1999a) was used to quantify LCC and to estimate annual isoprene emissions from SRC and other land cover types.

2.4 Study objectives

The purpose of this thesis was to map the temporal and spatial development of willow, poplar and rapeseed plantations during the time period between 2001 and 2014 and to determine the plot size and their distribution across Svealand and Götaland in Sweden. A Geographical Information System (GIS) used in this study offered a simple method to map and to quantify LCC from forest/agriculture land into SRC and to estimate BVOC isoprene annual turnovers caused by cultivation of thousands of hectares of SRC and other land cover types. In the case of rapeseed plantations, this study intends to investigate the temporal development of these plantations and will exclude the LCC quantification from agriculture/forest into rapeseed and their effects on air quality. Since, rapeseeds are non-isoprene emitters. The selection of SRC sites in the context of LCC and NO₂ levels distribution could support the decision making process to avoid or reduce the effects of LCC to SRC on air quality in Sweden. This model uses standard emission potentials of isoprene for different ecosystem types from the NatAir inventory (Steinbrecher et al., 2009) and isoprene standard emissions of willow and poplar from Merilo et al. (2005) and Slanina (1997). The used methodology to quantify the annual isoprene emissions was based on Simpson et al. (1999a), the Swedish average value of the integrated environmental factors i.e. light and temperature, for 12 months.

This study focuses on both willow and poplar plantations with potential to produce woody chips for energy production in CHP plants, and rapeseed which is used as liquid biofuels in the transport sector. The LCC from agriculture land into SRC will have bad consequences on air quality since SRC are recognized as high BVOC emitters, emitting isoprene in higher rates than other croplands (Copeland, Cape, and Heal, 2012) and eventually lead to O₃ formation to unhealthy levels (Carlton, Wiedinmyer, and Kroll, 2009). In the EU isoprene constitutes 28 % of the total BVOC emissions, forest land emits 41% isoprene, agriculture land emits 7 % and other land use emits 20% isoprene (Karl et al., 2009).

2.5 Hypotheses

This study was premised on the following hypotheses:

H I: The availability of CHPs infrastructure and the increased demand for bioelectricity and bio heat is growing year by year and available land suitable for biofuels feedstock, it is assumed that willow, poplar and rapeseed used areas have been increased between the time period 2001 and 2014. It is also assumed that the areas used for rapeseeds are larger than SRC because of the market for biodiesel in transport sector is larger than solid biomass

H II: As SRC are mainly cultivated on arable land we expect the occurred LCC is mainly from agricultural land into SRC because of its suitability for SRC cultivation

H III: It is assumed that released isoprene from SRC would form a large share of total isoprene emissions in the country in comparison to other land cover types

Chapter 3 Methodology and Data collection

3.1 Data Collection

The selected study area in this thesis was the Svealand and Götaland regions, the Norrland region was excluded since the climate and the soil type was not suitable for SRC and rapeseed cultivation. The soil characteristics in northern Sweden are not suitable for SRC, covered by 50% of Haplic and Podzols, (Greve et al., 1998). This type of soil is sandy with low pH levels and nutrients thus do not satisfy the requirements for SRC cultivation. Furthermore, low population density in Norrland and the supply from forest fuel and other renewable energy sources makes SRC less attractive option in this region. ArcGIS 10.3.1 which is founded by ESRI (Environmental Systems Research Institute) was used to generate the maps and GIS analyses for this study.

The block database of willow, poplar and rapeseed over the time period between 2001 and 2014 for the whole country was obtained from the Swedish Board of Agriculture (Jordbruksverket), to be analyzed with other datasets and carry out a spatial data analysis. The geographical data of willow, poplar and rapeseed plantations and its statistics were collected via emails and phone interviews conducted in October 2015 with the Swedish Agriculture Board and the GIS support department (L. Bäckström, personal communication, October 2015) and the Board's data warehouse (DAWA) which coordinates the department's statistics. The data included the parcel 'ids' of each plantation in the corresponded year over the period between 2001 and 2014 delivered in excel spreadsheets, and its geographical data in form of geographical vector data. Data with missing parcel ids or non-matching ids with the provided geographic data were discarded. All of the data were projected into "SWEREF99". The Swedish Land Cover Data or Svenska Marktäckedata (SMD, 2015) is a product of the CORINE Land Cover (CLC) data of 2006, 2012 and LCC 2006-2012 covering 35 land type classes, main classes are artificial areas, agricultural areas, forest and semi-natural areas, wetlands and water bodies across Sweden which obtained from LANTMÄTERIET.

The distribution of particulate matter map (PM_{10}) and NO_2 levels in ambient air (figure 1) were both modeled by Simulation Air (SIMAIR) at the Swedish Meteorological and Hydrological Institute (SMHI), representing annual mean values of PM_{10} and NO_2 concentration over Sweden in 2010. The used model is composed of the Multi-scale Atmospheric Transport and Chemistry (MATCH) to assess air quality in Sweden as input to the Background Urban Model (BUM) estimating PM_{10} and NO_2 urban background levels with 1km x 1km grid resolution (De Smet et al., 2013). The obtained data were in form of geographical vector data which was converted into

raster grid with 30 m x 30 m resolution. Population density data in 2000 (figure 1) was obtained from Center for International Earth Science Information Network (CIESIN, 2005). In addition to, the collected data of 22 CHP plants for biofuels in Sweden in (Sweden/Biomass, n.d.) were obtained in form of XYZ coordinates and digitized (figure 1) in the GIS software. GIS analysis and statistics were carried out to map SRC and rapeseed and to provide a clear profile of their distribution over time with respect to location, LCC, plot size. Furthermore, to quantify SRC used areas within different NO₂ levels and draw conclusion of isoprene annual turnovers from planted SRC in comparison to other land uses in Sweden.

Table 1 Vegetation class, foliar biomass densities are derived from individual crop species in the plant composition list (EMEP/CORINAIR, 1999), isoprene standard emission potentials were adopted from the NatAir inventory (Steinbrecher et al., 2009)

| CLC(2006)/Vegetation class | Density (g/m ²) | Standard Isoprene emission rate (μg g ⁻¹ h ⁻¹) | Plant Composition |
|---------------------------------------|-----------------------------|---|------------------------------------|
| 211 Non-Irrigated Arable Land | 800 | 0.5 | Durum Wheat |
| 222 Fruit trees and berry plantations | 250 | 0.5 | Fruit tree and berry plantations |
| 231 Pastures | 400 | 0.5 | Fodder and other on arable land |
| 242 Complex Cultivation Patterns | 330 | 0.5 | 50% Dry Pulses, 50% Rye |
| 243 Agriculture, with natural Veg. | 600 | 0.5 | a , 50% Rye |
| 311 Broad-Leaved Forest | 360 | 15 | b |
| 312 Coniferous Forest | 950 | 3 | c |
| 313 Mixed Forest | 660 | 10 | 50% Broad-Leaved, 50% Coniferous |
| 321 Natural Grassland | 420 | 0.5 | Grassland |
| 322 Moors and Heathland | 350 | 10 | moorland/heathland |
| 324 Transitional Woodland-Shrub | 400 | 5 | d |
| 333 Sparsely Vegetated Areas | 140 | 0.5 | 30% Green Urban Areas, 50% no veg. |
| Rapeseed | 400 | 0 | rape |

(a) 50% *Non-permanent crops*; (b) 15% *Fagus sylvatica*, 10% *Q. ilex*, 10% *Betula pubescens*, 10% *Q. robur*, 10% *Q. pubescens*, 10% *Q. petraea*, 20% *Eucalyptus*, 5% *Juglans regia*; (c) 40% *Pinus sylvestris*, 40% *Picea abies*, 20% *Pinus pinea*; and (d) 30% *Q.ilex*, 30% *Q. coccifera*, 30% *Arbutus unedo*, 10% *Myrtus communis*.

Table 2 Isoprene standard emissions for controlled and fertilized willow plantations under sunlight and shade conditions and poplar, specific leaf area (SLA) and leaf area index (LAI) estimations for foliar density

| Species | SLA m ⁻² g | LAI m ² /m ² | D: LAI/SLA g m ⁻² foliar density | reference | Standard emission rate (μg G ⁻¹ DW h ⁻¹) | reference |
|---------|-----------------------|------------------------------------|---|-----------|---|-----------|
| | | | | | | |

| | | | | | | |
|--|----------------------------|-------------------|---------------------|--------------------------|------------------------------------|---------------------------|
| Willow <i>Salix viminalis</i> Västergötland, Sweden | Fertilized 0.0144 | Fertilized 4.9 | Fertilized 340.2 | Merilo et al., (2005) | 7 Method: Canopy- scale, REA | Olofsson et al. (2005) |
| Poplar (P. <i>trichocarpa</i>) | 0.017 BETYdb, (2010) | 3.8 | 223.5 | Slanina(1997) | 53 | Slanina(1997) |

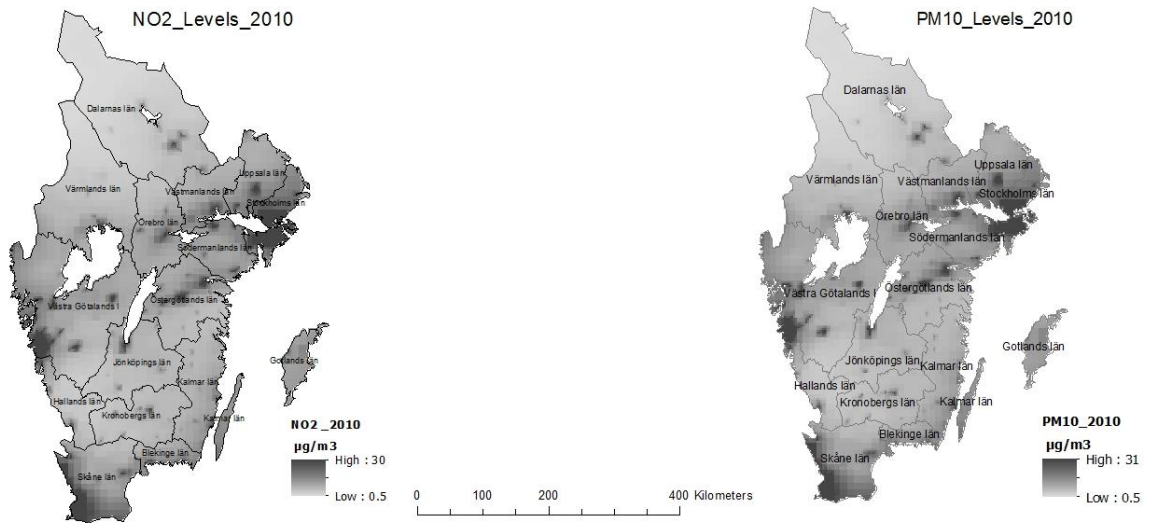
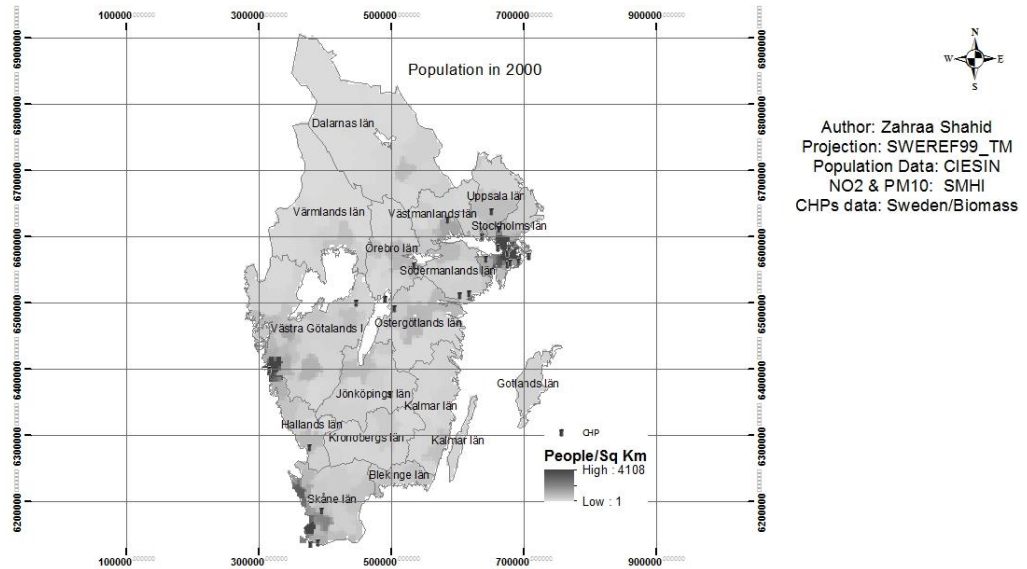


Figure 1 Map of population density in 2000 People/km² (CIESIN, 2005), distribution of NO₂ ranges 0.5 - 30µg/m³ and PM₁₀ levels range 0.5 - 31µg/m³ over Svealand and Götaland in 2010 (De Smet et al., 2013), and 22 CHPs for biofuels (Sweden/Biomass, n.d.)

3.2 Estimations of isoprene emissions using a seasonal approach

The foliar densities of the selected willow plantation in this study were adopted from Swedish clones in western Sweden, which have been used for experimental comparison between fertilized and non-fertilized soils (Merilo et al., 2005). However, the values of standard canopy-level emission for willow was adopted from Olofsson et al. (2005) which was based on the average of the entire canopy under sunlight and shaded conditions. The conventional isoprene emission rate (F) is calculated based on a simplified methodology that used the European Monitoring and Evaluation Program (EMEP) data to calculate seasonal or monthly isoprene emissions (Simpson et al., 1999a). This simplified methodology is a modification of an hourly system method adopted from Guenther et al. (1996) that is used in the MEGAN model in the original study and then modified to be seasonally or monthly based method.

The following equations 9, 10 and 11 illustrate the isoprene flux calculations:

$$F = E * D * C_L * C_T \quad (9)$$

Where F is the isoprene flux ($\mu\text{g m}^{-2}\text{h}^{-1}$) estimation, E is the isoprene standard emission rate ($\mu\text{g g}^{-1}\text{dry foliar mass h}^{-1}$) at leaf temperature of 30 °C and at PPFD flux of 1000 $\mu\text{mol m}^{-2}\text{s}^{-1}$, D is the foliar density ($\text{g dry foliar mass m}^{-2}$) which is estimated through dividing LAI by the specific leaf area (SLA), CL and CT are dimensionless empirical terms that modulate the isoprene emissions in response to incident PPFD and leaf temperature respectively (Guenther et al., 1993).

The hourly variations in isoprene emissions were estimated using ISOG algorithm from Guenther et al. (1993):

$$\gamma_{iso} = C_T * C_L \quad (10)$$

Environmental factors of temperature and PPFD for isoprene are calculated as following:

| Isoprene (Tingey et al., 1991) | Correction factor for temperature C_T | Correction factor for light C_L |
|--------------------------------|--|---|
| | $\frac{95000(T-30)}{e^{2520.3891*(T+273.15)}}$ | $\frac{0.0028782 PPFD}{\sqrt{1+0.00000729 PPFD^2}}$ |
| | $\frac{230000(T-40.85)}{1+e^{2520.3891*(T+273.15)}}$ | |

$$\mathbf{F} = \mathbf{E} * \mathbf{D} * \mathbf{\Gamma} \quad (11)$$

Γ is the integrated value of hourly γ_{iso} dependent on leaf temperature and PPFD factors seasonally or monthly. The meteorological data from the EMEP Meteorological Synthesizing Centre-West (EMEP MSC-W) models Γ obtained for 6 months (May-October) and for 12 months over each country modeled from hourly isoprene γ_{iso} values. The Swedish average value of the integrated environmental factors of isoprene for 6 and 12 month are 315 hours and 368 hours respectively.

The monthly Γ was calculated based on several assumptions; PPFD factor in equation 10 was assumed to be 1 during the morning hours when PPFD reach $1000 \mu\text{mol m}^{-2}\text{s}^{-1}$ with a threshold value for defining the day length as $200 \mu\text{mol m}^{-2}\text{s}^{-1}$, and 0 was the value set for the rest of the day; the temperature factor was not calculated on hourly basis rather it was an approximation of a monthly average daytime temperature which introduces much less uncertainties than in the emission potentials. The number of light-hours per day is a function of latitude and month where the length of the day was calculated at the 15th of each month from 80°N to 36°N latitudes (Simpson et al., 1999a).

The yearly Γ (hours) value of isoprene over each country is calculated as following:

$$\mathbf{\gamma}_{iso} = \mathbf{T}_{mm} * \mathbf{N}_d(\text{mm}) * \mathbf{N}_L(\text{mm}) \quad (12)$$

Where T_{mm} the monthly mean temperature in each month, N_d (mm) is the number of days per month and N_L (mm) is the number of light-hours per day and “mm” is month.

The final calculation of annual isoprene turnover in Sweden was estimated using the following equations:

$$\mathbf{F} = \text{willow or poplar used area} * \mathbf{E} * \mathbf{D} * \mathbf{\Gamma} \quad (13)$$

$$\mathbf{D} = \frac{\text{LAI}}{\text{SLA}} \quad (14)$$

The program flow in figure 2 is used in this example, the used area of willow estimated to be 9000 ha in 2014 (figure 3A), isoprene standard emission rate of willow (*S. viminalis*) is $7 \mu\text{g g}^{-1}\text{dw h}^{-1}$, foliar density is 340 g/m^2 (table 2) and Γ for 12 months in Sweden is 368 hours (equation 13 and 14):

$F = 90390000 \text{ m}^2 * 7(\mu\text{g g}^{-1}\text{dw h}^{-1}) * 340 (\text{g m}^{-2}) * 368 (\text{h}) = 79167177600000 \mu\text{g yr}^{-1}$ or 87.3 ton yr^{-1} for the total willow used area.

The standard emission rate of willow (*S. viminalis*) was adopted from observed values in Olofsson et al. (2005) case study in western Sweden. The maximum emissions were observed at 12:00 daytime was up to $0.98 \mu\text{g m}^{-2} \text{ s}^{-1}$ in July at 303K and $1000 \mu\text{mol m}^{-2} \text{ s}^{-1}$ PPFD.

In this study average of maximum canopy emission measurements is $0.65 \mu\text{g m}^{-2} \text{ s}^{-1}$ ($2340 \mu\text{g m}^{-2} \text{ h}^{-1}$) for three months June, July and September observations for the sun exposed and shade leaves. The values obtained during the measurements were $18 \mu\text{g m}^{-2} \text{ s}^{-1}$ for June, $98 \mu\text{g m}^{-2} \text{ s}^{-1}$ for July and $78 \mu\text{g m}^{-2} \text{ s}^{-1}$ for September and then were normalized by foliar density (340.2 g m^{-2}) value of the fertilized plantations, which resulted in $7 \mu\text{g g}^{-1}\text{dw h}^{-1}$ as standard emission rate of willow (*S. viminalis*) that was used to calculate the final annual isoprene emissions for this present study.

The foliar density of willow (*S.viminalis*) in response to fertilization was calculated by dividing LAI by SLA values of the plantation, which were based on Merilo et al. (2005) case study. In that study, they used fertilizers that have been added on annual basis to willow (*S.viminalis*) clones. An about 160 kg nitrogen (N) per ha, 37kg phosphorus (P) per ha and 70 kg Potassium (K) per ha were added to a 6*16 m² plot. Also, the leaf measurements in response to fertilization were carried out during June-September with a daily average temperature between 3 and 10.7 °C between 10:00-16:00 h. The healthy plant leaves under sunlight were the ones growing in the uppermost foliage quarter and shade leaves are those in the lowest foliage quarter (Merilo et al., 2005).

In figure 2 a GIS methodology is followed to calculate isoprene emission capacities from SRC and CLC and to map the fluxes over this study area by using different land uses data. A classification of biofuel crops data blocks into three groups was carried out. Input parameters were assigned to SRC plantations and CORINE land cover data listed in Table 1 and Table 2. ESRI ArcGIS software was used to calculate the annual F of willow and poplar and other vegetation by assigning E, D and Γ for each polygon (equation 13 and 14). This approach creates a set of polygons with different values contain information of isoprene turnover yearly over the study area. The foliar densities derived from individual crop species in the plant composition list (EMEP/CORINAIR, 1999) and standard isoprene rates for each forest type were adopted from the NatAir inventory (Steinbrecher et al., 2009) (Table 1). Fertilized willow (*S. viminalis*) and poplar (*p. trichocarpa*) standard isoprene rates and foliar densities were used from Table 2. The estimated LCC from agriculture/forest into SRC was calculated using different geoprocessing tools in ArcGIS software.

In order to carry out the GIS analysis, preparing the datasets, CORIN, biofules plantations and NO₂ levels, was done through different geoprocessing tools such as join, clip, merge and reclassifying the plots size as it is illustrated in figure 2. Join tool was used to join geographic

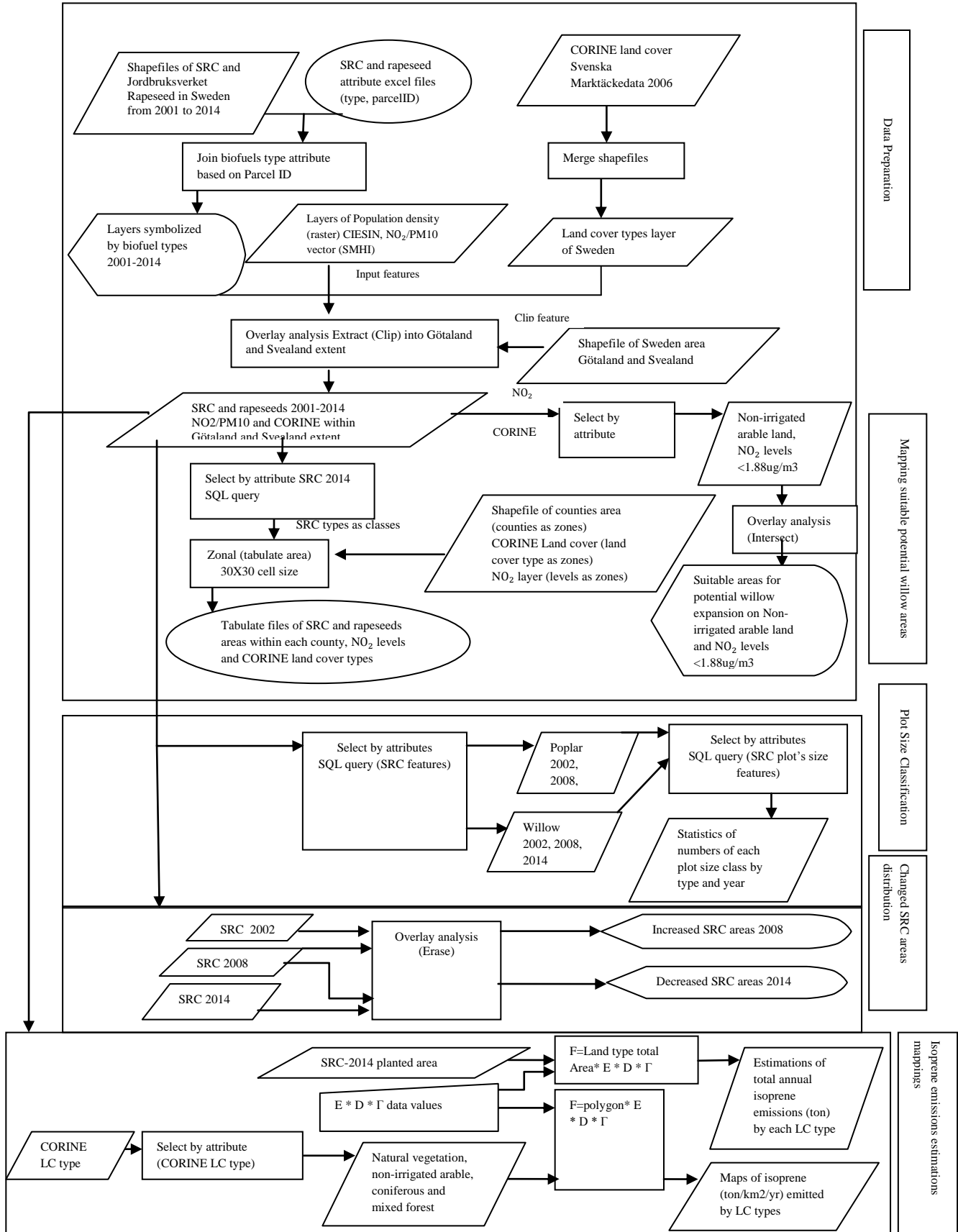
features of SRC to SRC attribute data in excel file based on the parcel IDs that is found in both tables, in order to use the biofuels data types and analyze the layers' features

Estimations of LCC from agriculture/forest into SRC and exploring the distribution of biofuels area relative to different land cover types, two different of data sets were used for that purpose.

The land cover types CORINE dataset as a zone layer and biofuels datasets as data inputs of zonal tool (tabulate area) to determine the area of biofuels areas for each land cover type value.

Also the distribution of SRC areas for each NO₂ value was estimated using the same method and datasets used, NO₂ and SRC as data inputs. Also overlay analysis such as intersect tool was used to detect the distribution of annual isoprene emitted zones under different NO₂ values.

In addition to that to analyze the differences in SRC used areas and visualize the changed areas of SRC over 2002, 2008 and 2014 years, the SRC datasets of those years were used as inputs, geoprocessing tools (Erase) was used to explore the increased SRC areas in 2008 and the decreased areas in 2014.



Chapter 4 Results

In this section the results of the GIS analysis for poplar and rapeseed temporal development over the time period between 2001 and 2014, and willow over the time period between 2002 and 2014 is shown in forms of tables, figures and maps. SRC plot size classes during 2002, 2008 and 2014 are also introduced in this chapter besides LCC and share of willow and poplar plantations of total agriculture land, forest land and other land cover types. The temporal development of annual isoprene emission from SRC and isoprene emissions due to LCC from forest / agriculture land into SRC were estimated.

4.1 Short Rotation Coppice and Rapeseeds temporal development

The temporal development of SRC and rapeseed used areas in hectares over the time period from 2001 to 2014 is shown in figures 3A and 3B within Svealand and Götaland regions. The data of willow used areas in 2001 is missing and was not presented throughout the study. A decline of willow used areas starting from 2002 to 2014 is about 65% and that's about 16900 ha. Poplar used areas had increased over the time period between 2001 and 2014 with about 90% equals to 1400 ha. In figure 3B the area that is used for rapeseed shows an increase by 70% whereas spring variation had declined by 60% over the time period between 2001 and 2014. Tables 3 and 4 represent the percentage change of used areas of SRC and rapeseed in 2002, 2008 and 2014. The selected time period was based on observation from figure 3A and figure 3B to analyze the first and second half of the period in relation to studied data, since there is a clear rise in the used areas of willow and rapeseed areas in total from 2002 to 2008, and then a trend of decreasing from 2008 to 2014 except for poplar used areas which shows an increase during both time periods. The planted areas of different energy crops are presented in table 3 over 2002 and 2008. The change of each crop planted areas is also shown as percentage with most of them show an increase in 2008 compared to 2002. In table 4, the energy crops are presented for 2008 and 2014. The change of each crop planted areas is also shown as percentage with most of them show a decline in 2014 compared to 2008 except poplar plantations.

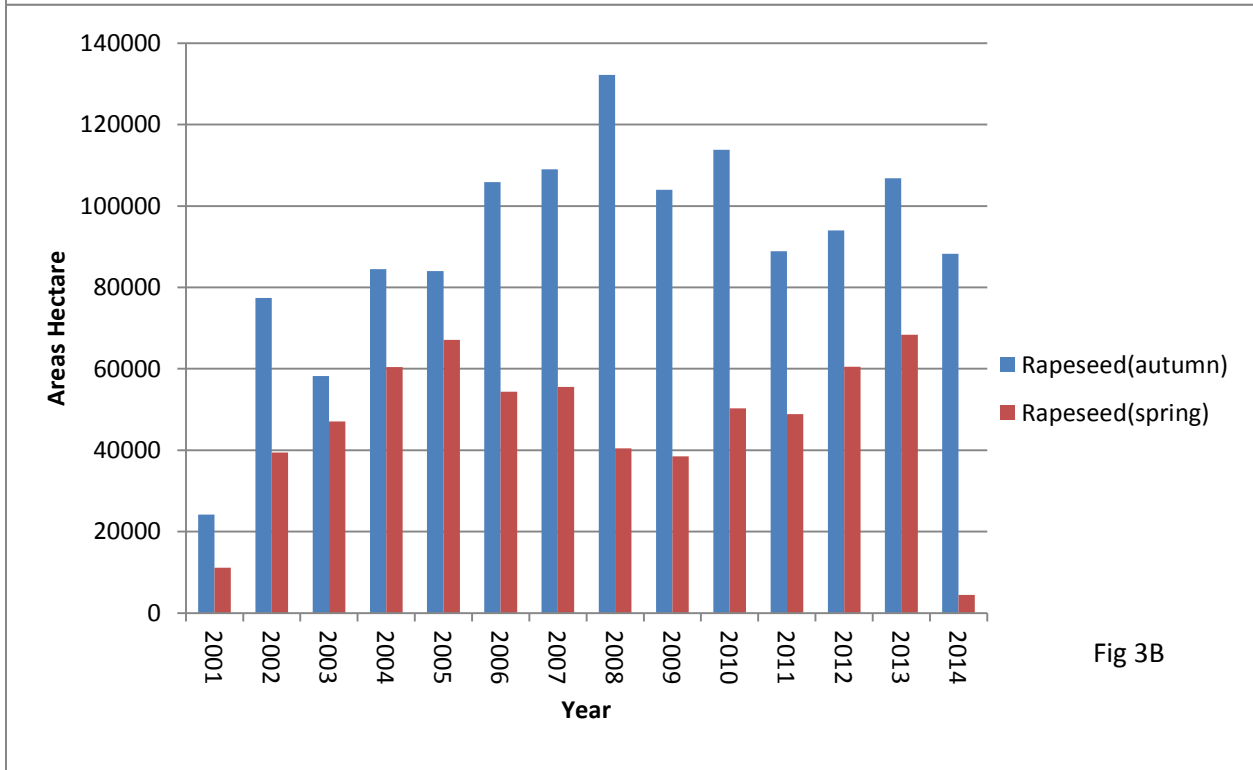
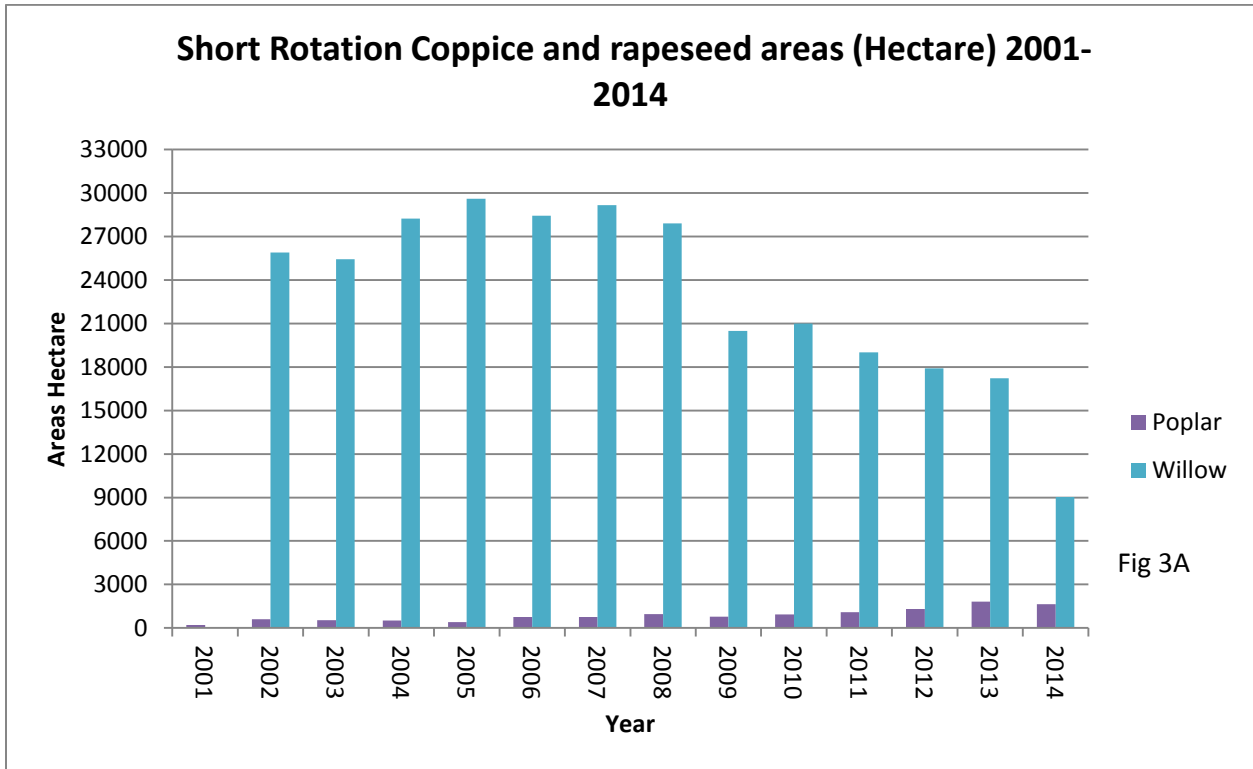


Figure 1A and 3B Areas (ha) of willow, poplar and rapeseed areas in Svealand and Götaland between the time period 2001 and 2014

Table 3 Temporal development of willow, poplar and rapeseed areas (ha) in Sweden between 2002-2008

| Energy crops | Planted area (ha) 2002 | Planted area (ha) 2008 | Change (ha) | (%) Change |
|----------------------|---------------------------|---------------------------|-------------|------------|
| Willow | 25952 | 27901 | 1949 | +7% |
| Poplar | 582 | 951 | 369 | +39% |
| Rapeseed (autumn) | 77434 | 132196 | 54762 | +41% |
| Rapeseed (spring) | 39367 | 40500 | 1133 | +3% |

Table 4 Temporal development of willow, poplar and rapeseed areas (ha) in Sweden between 2008- 2014

| Energy crops | Planted area (ha) 2008 | Planted area (ha) 2014 | Change (ha) | (%) Change |
|----------------------|---------------------------|---------------------------|-------------|------------|
| Willow | 27901 | 9039 | 18862 | -68% |
| Poplar | 951 | 1632 | 681 | +42% |
| Rapeseed (autumn) | 132196 | 88269 | 43927 | -33% |
| Rapeseed (spring) | 40500 | 4497 | 36003 | -89% |

4.2 Short Rotation Coppice plots size

The land size classification method was adopted from the Swedish agriculture ministry parcel size classification for willow in 2007 (Jordbruksverket, 2008), and has been used for willow and poplar plantations during 2002, 2008 and 2014 in this study. The selected years were based on the observed trend of the used area that is shown from the above results in relation to the changed use of SRC between 2002-2008 and 2008-2014 (tables 3 and 4). In this study area there were about 2340 willow plots in 2002, 3000 in 2008 and 2500 in 2014. About 50% of the willow planted areas are composed of 20 ha plot size or larger in 2002 and 2008 (figure 4A) with most of them distributed in Skåne and Uppsala region.

In 2014 the number of willow plots with size 6 -10 ha were about 375, distributed over 15 counties as following; Örebro 44, Östergötland 26, Skåne 71, Södermanland 60, Stockholm 18, Uppsala 66, Värmland 7, Västmanland 39 and Västra Götaland 27, Blekinge 2, Dalarna 5, Götland 1, Halland 2, Jönköping 1 and Kalmar 5. There were also about 47 poplar plots with size 6-10 ha distributed over 9 counties as following Blekinge 1, Halland 2, Kronoberg 1, Östergötland 6, Skåne 17, Södermanland 6, Uppsala 1, Västmanland 8, Västra götland 5.

In 2014, the number of plots of size 20 ha or larger declined rapidly to cover only 4% of the total willow planted area (table A4) with most of them distributed in Uppsala. Only 20 willow plots were recorded to have plot size between 20 and 40 ha in central eastern counties, and the largest found in Uppsala and other two in Skåne.

Regarding poplar plantations, the number of plots had largely increased from 2002 till 2014 (figure 4B). There were only about 42 plots covering 600 ha in 2002, 127 plots covered 950 ha in 2008 (figure 4D and table A6) and 764 plots covered about 1600 ha in 2014 (figure 4D and table A7). The largest poplar plots are between 20 and 31 ha and located in Västmanland, Södermanland, Kalmar and Östermanland. Tables about the number of plots of each size class of willow and poplar in 2002, 2008 and 2014 are shown in the Appendix (tables A2 to table A6).

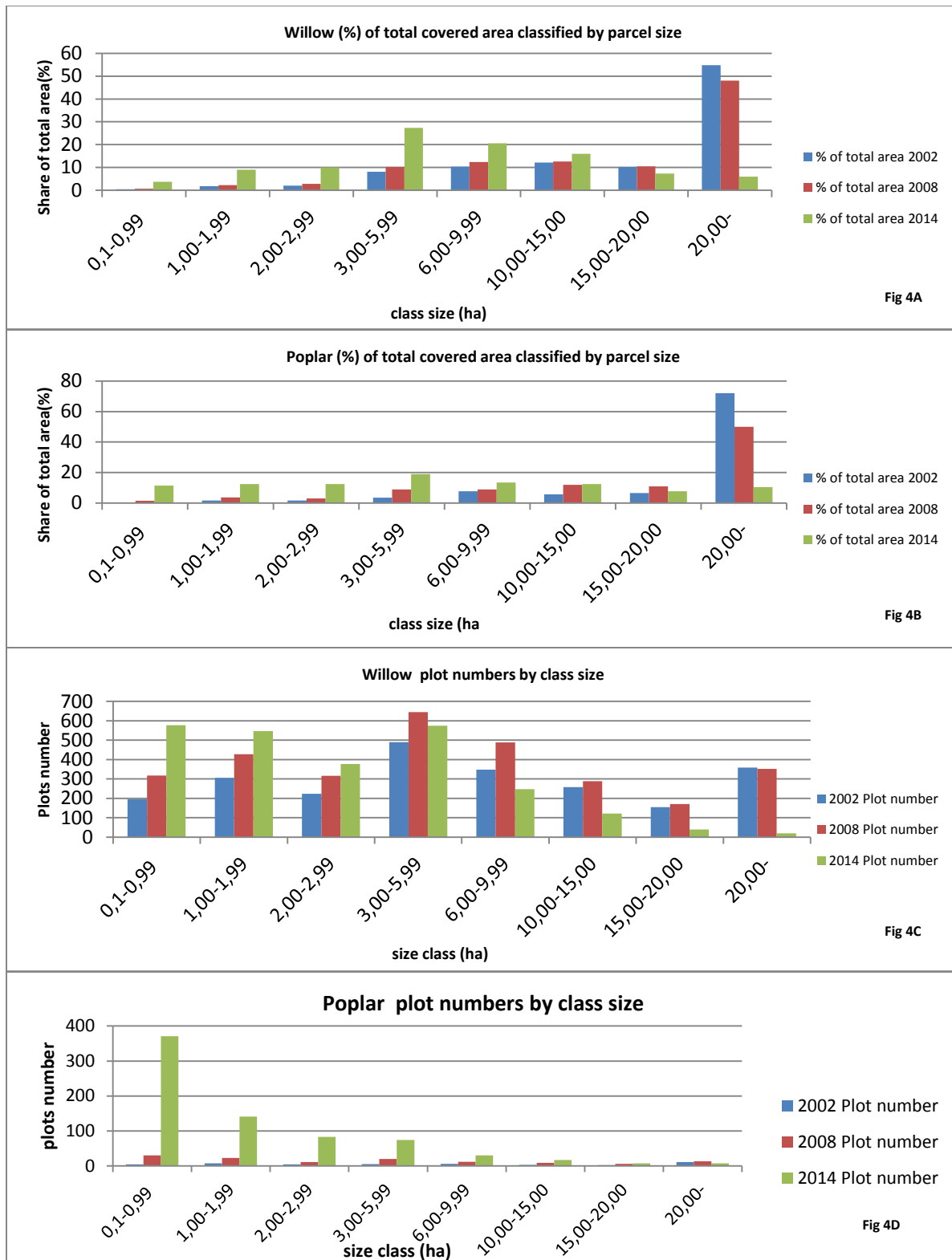


Figure 4 A and B show willow and poplar share of total planted area in each classified parcel size; 0.1-0.99 ha, 1-1.99 ha, 2-2.99 ha, 3-5.99 ha, 6-9.99 ha, 10-15, 15-20, >=20 ha in Sweden during 2002, 2008 and 2014, figure 4C and D show the number of plots of willow and poplar by each plot class

4.3 Short Rotation Coppice and land cover change

In 2011 the share of agricultural land which is composed of arable land, under permanent crops and pasture is about 7.47% of total land area in Sweden and the share of non-irrigated arable land is 6.6% of total land area (World Bank Indicators, 2016) and 76% of the total agriculture land in Svealand and Götaland regions (Table 5). The changed land into SRC in Table 6 shows that non irrigated-arable land is the largest share of agriculture land that used to cultivate willow and poplar plantations. The converted land into willow is estimated 0.5% and 0.2% of the total non-irrigated arable land in 2002 and in 2014 respectively (Table 6).

Table 5 Agriculture land cover types (2006) within study area

| Agriculture land types | Area (ha) | Land type % of total agriculture area |
|---|-----------|---------------------------------------|
| Complex cultivation patterns | 198033 | 3 |
| Fruit trees and berry plantations | 3085 | 0.05 |
| Land principally occupied by agriculture, with significant areas of natural vegetation' | 9 573 33 | 15 |
| Non-irrigated arable land | 4 889 871 | 76 |
| Pastures | 3 775 77 | 6 |

Table 6 LCC from agriculture land into SRC as share of willow and poplar plantations of total agriculture land cover types within Svealand and Götaland regions in 2002 and 2014

| Agriculture land types | Willow % 2002 | Willow % 2014 | Poplar % 2002 | Poplar % 2014 |
|--|---------------|---------------|---------------|---------------|
| Non-irrigated arable land | 0.5 | 0.2 | 0.01 | 0 |
| Fruit trees and berry plantations | 0.1 | 0 | 0 | 0 |
| Pastures | 0.05 | 0 | 0 | 0 |
| Complex cultivation patterns | 0.04 | 0.04 | 0 | 0.02 |
| Land principally occupied by agriculture, with significant areas of natural vegetation | 0.04 | 0.03 | 0 | 0.01 |

The non-irrigated arable land size areas were estimated from CLC 2006 (SMD, 2015) and shown by each county within this study area figure 5 while the share of SRC plantations of total planted areas are shown in the Appendix (figure A1). Södermanland, Skåne and Västra Götaland are the top three counties that have the largest areas of non-irrigated arable land and the largest areas used for SRC were located in these counties.

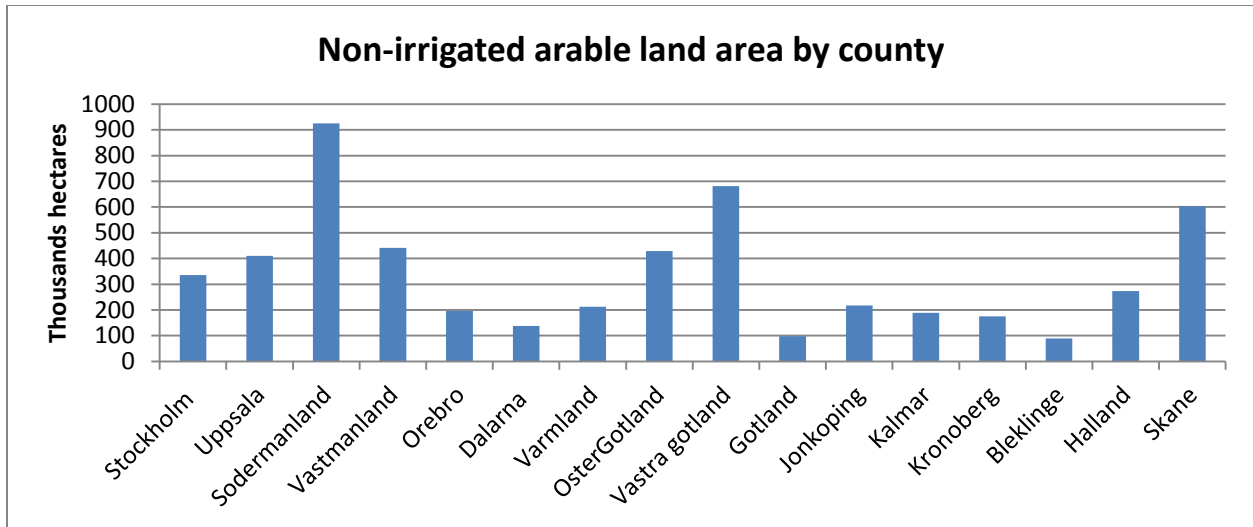


Figure 5 Area of non-irrigated arable in 2006 (Thousands hectares) within study area

There is an increase in the converted areas from non-irrigated arable land into SRC plantations in 2008 after which the LCC decreased until 2014. Figure 6 presents the temporal development of the share of SRC plantations of the total non-irrigated arable land. In 2014, the size of non-irrigated arable land that is turned into willow plantations within that time period has been decreased by 70% compared to what it was in 2008 while area that had been converted into poplar increased by 50% in 2008 and in 2014. On the other hand, the largest areas of pasture land (figure 7) are in Skåne, Kalmar and Västra Götaland and in the southern eastern counties where the SRC plantations have the lowest share of planted areas as it shown in figure A1.

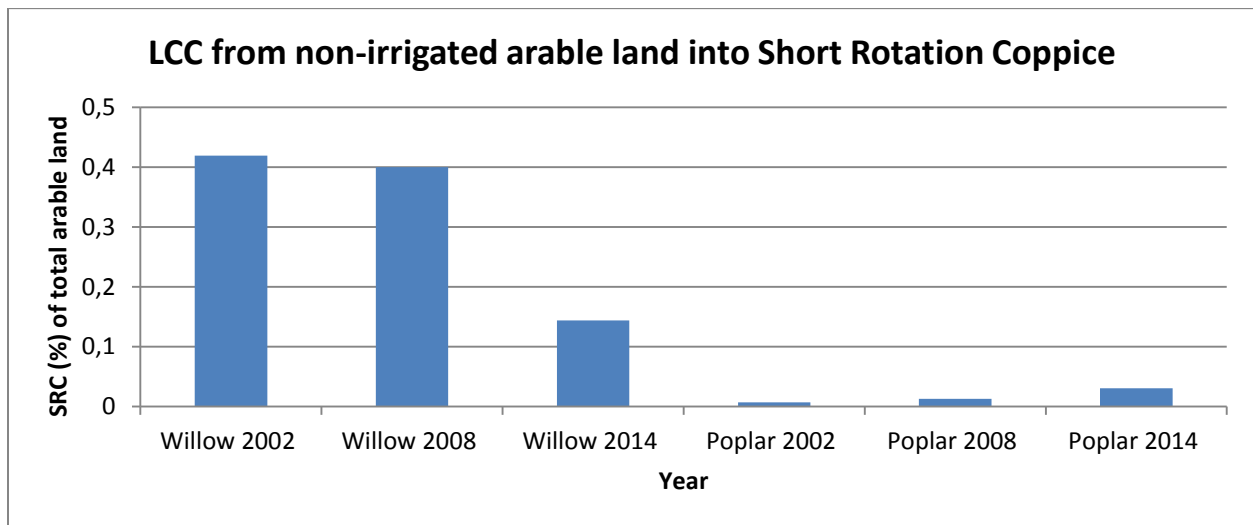


Figure 6 Temporal development of willow and poplar used areas shown as used area percentage of total non-irrigated arable land in 2002, 2008 and 2014 within study area

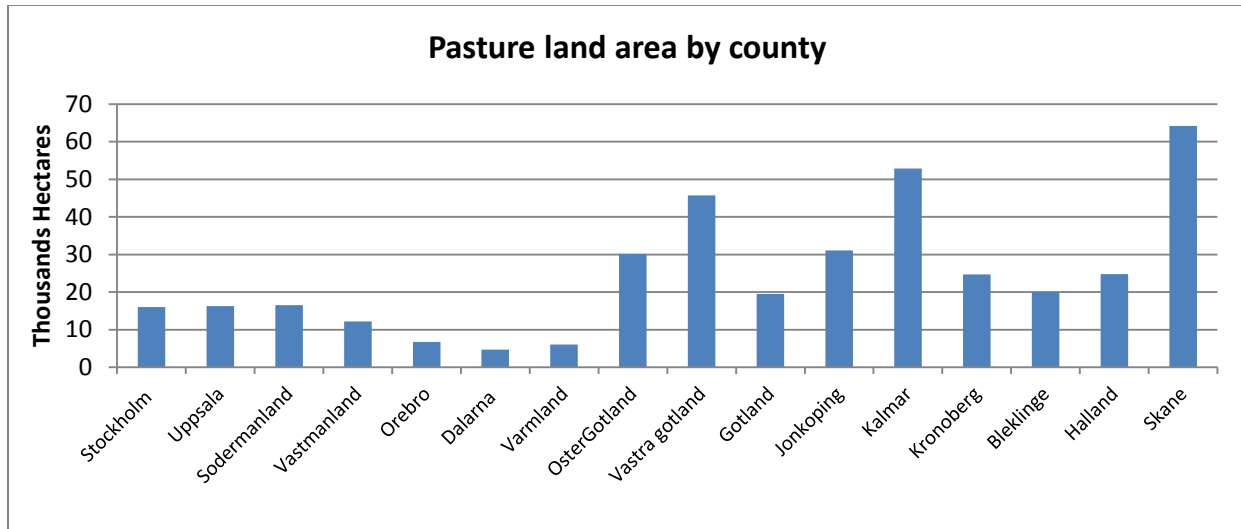


Figure 7 Area of pasture land in 2006 (Thousands hectares) within study area

In figure 8 presents the temporal development of pasture land that turned into SRC plantations in 2002, 2008 and 2014. The changed pasture land into willow has increased in 2008 compared to 2002, and then the total pasture land used for willow had been decreased in 2014 by 50% compared to 2008, while changed land into poplar areas has increased by 50% in 2014. The total pasture land areas converted to willow were only 366 ha in 2002 within this study area. On the other hand, the LCC from pasture to poplar show an increase during 2008 and 2014.

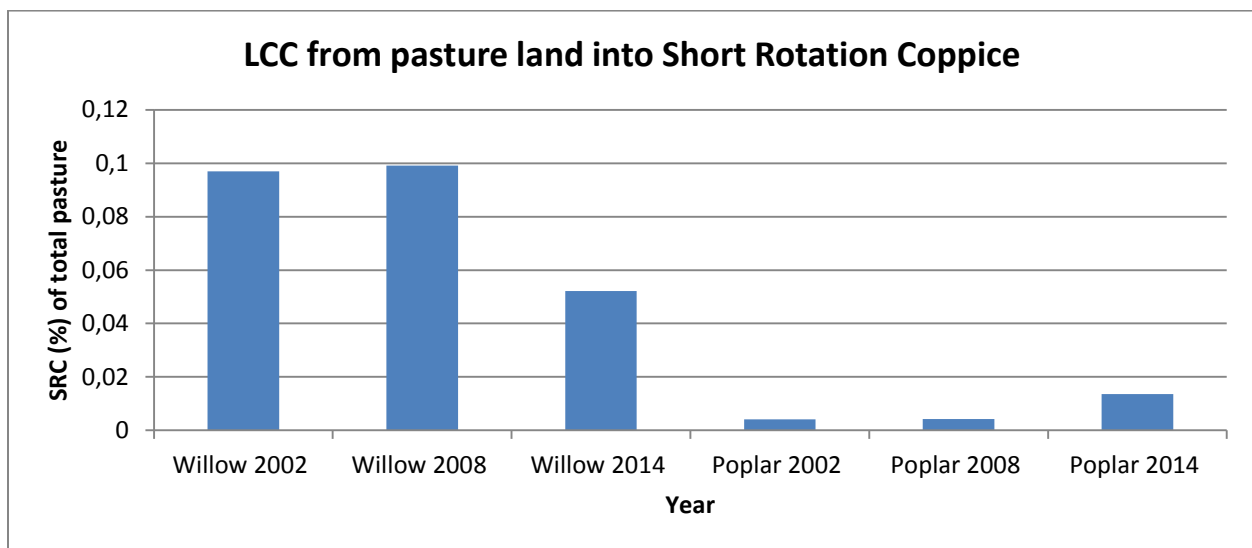


Figure 2 Temporal development of willow and poplar used areas shown as used area percentage of pasture land in 2002, 2008 and 2014 within study area

Forest land in Sweden forms about 68.7% of total land area according to World Bank Indicators (2016), and dominated by coniferous forest which covers 80% of the total forest areas and the other types of forest land forms small percentage of total forest areas (Table 7). The GIS results showed that the land converted from forest into SRC is very small compared to the changes from agriculture land into SRC. However, LCC from forest to willow in 2014 has increased compared to 2002 and to poplar has increased from almost nothing in 2002 to about 500 ha in 2014 (Table 8).

Table 7 Forest land cover types (2006) within study area

| Forest land types | Area (ha) | Land type % of total forest area |
|-----------------------------|-----------|----------------------------------|
| Bare rocks | 8459 | 0.03 |
| Beaches, dunes, sands | 85 | 0.0003 |
| Broad leaved forest | 958478 | 4 |
| Burnt areas | 746 | 0.002 |
| Coniferous forest | 20028824 | 80 |
| Mixed forest | 1162348 | 5 |
| Moor and heathland | 150208 | 0.6 |
| Natural grasslands | 2889 | 0.01 |
| Sparsely vegetated areas | 41921 | 0.2 |
| Transitional woodland-shrub | 2650389 | 11 |

Table 8 Size of LCC (ha) from forest to willow and poplar plantations in 2002 and 2014

| Forest classes | LCC to Willow (ha) 2002 | LCC to Willow (ha) 2014 | LCC to Poplar(ha) 2002 | LCC to Poplar(ha) 2014 |
|-----------------------------|-------------------------|-------------------------|------------------------|------------------------|
| Broad-leaved forest | 81 | 58 | 0.72 | 43 |
| Coniferous forest | 583 | 886 | 7.6 | 400 |
| Mixed forest | 122 | 186 | 2 | 26 |
| Transitional woodland-shrub | 38 | 76 | 0 | 55 |
| Total | 824 | 1206 | 10.32 | 524 |

The total forest areas and semi natural areas form about 4,890,000 ha (figure 9), the largest areas of forest land are located in the southeastern counties and these counties have the lowest percentage of SRC plantations compared to other counties within this study area (figure A1). The total changed forest land into SRC was about 1700 ha in 2014 (Table 8).

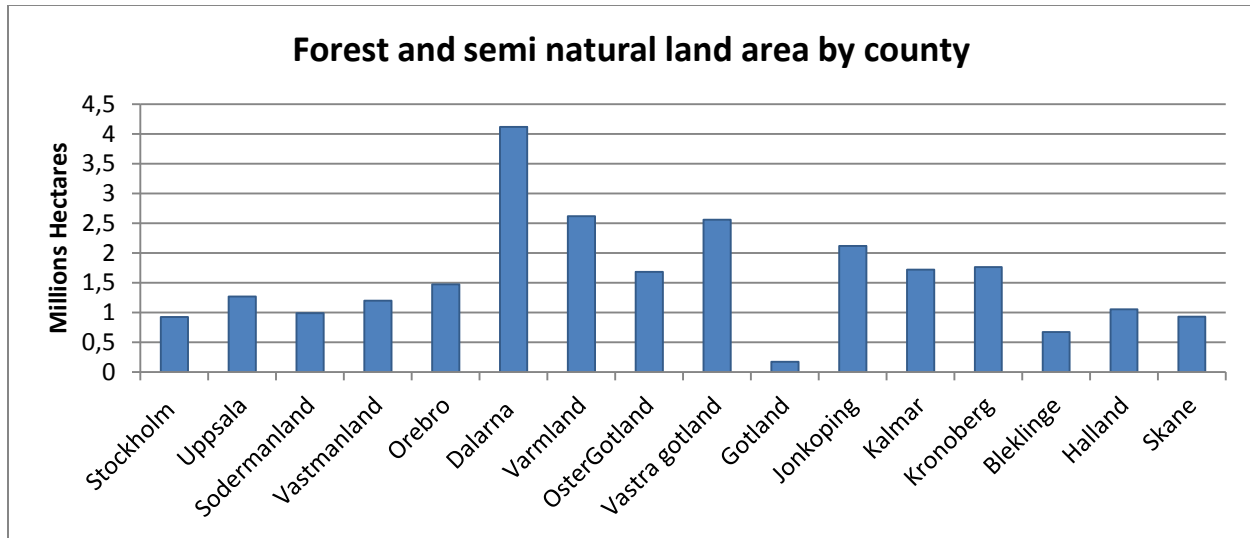


Figure 3 Area of forest and semi natural land in 2006 (Millions hectares) within study area (SMD, 2015)

The temporal development of the changed areas from different CORINE land cover types into SRC and rapeseed plantations in 2002 and 2014 within this study area are shown in figure 10 and figure 11. There was about 16 CORINE land cover types in Svealand and Götaland region were changed into willow plantations covered about 26000 ha in 2002. Non-irrigated arable land turned into willow formed about 18% and 10% of the total changed area in 2002 and 2014 respectively. There was about 1600 ha of LCC happened from non-irrigated arable land and coniferous into poplar in 2014. On the other hand, the LCC from non-irrigated arable land into rapeseed plantations was about 82% of the total changed non irrigated arable land and that corresponded to 112000 ha of land covered by rapeseed in 2002 (figure 10). In 2014, the size of changed area has dropped down into 90,000 ha, yet that still the largest land change that took place compared with other types of land cover.

The spatial distribution of SRC as it shown in figure 12 during 2002, 2008 and 2014 does not show a significant change in the selection of SRC sites, the most widely areas used for SRC was in the southern and central eastern parts of the Svealand and Götaland regions even though their development were changed during the last 12 years. The GIS analysis also indicates other types of LCC that took place where there is about 9000 ha were converted from arable land into other types of land use between 2006 and 2012; about 4000 ha were converted into artificial surfaces including roads, rails, airports urban areas and etc. and more details found in appendix (table A1). Also, 1200 ha converted into pastures and 1150 ha into transitional woodland-shrub.

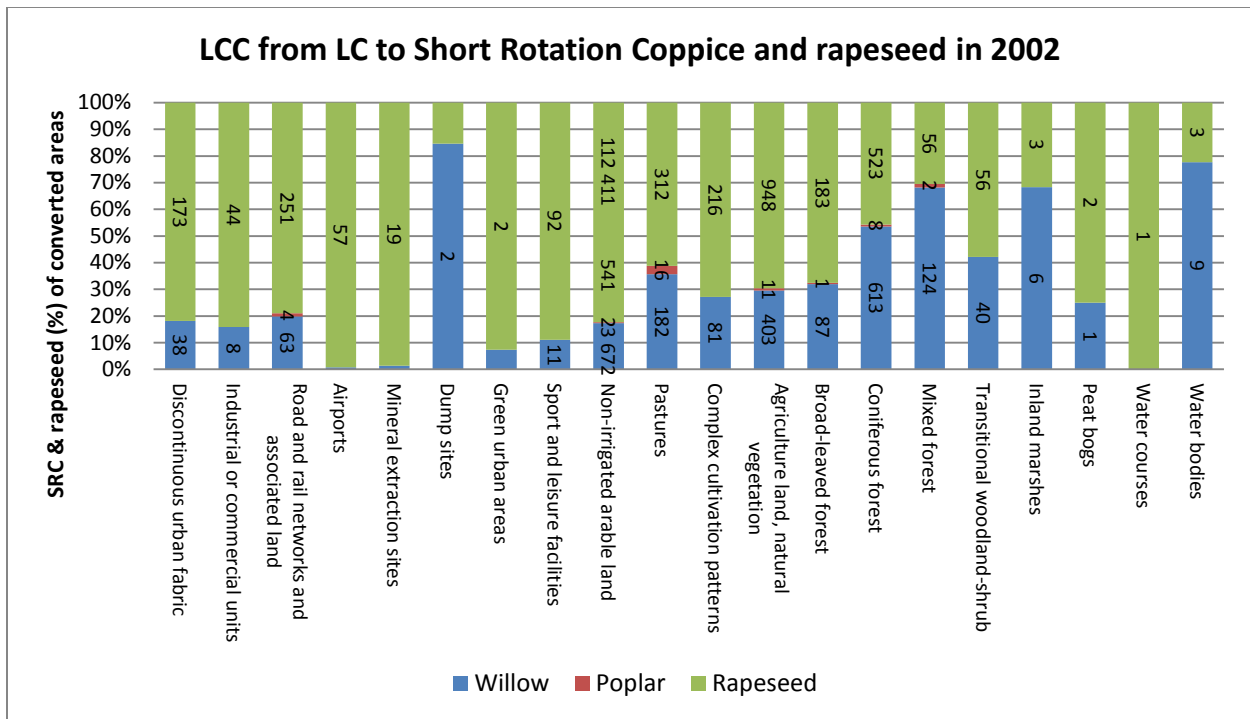


Figure 10 Areas of LCC from different land cover types to Short Rotation Coppice and rapeseed in 2002 within study area (ha) are shown on each column and share of SRC and rapeseed of total converted areas (%)

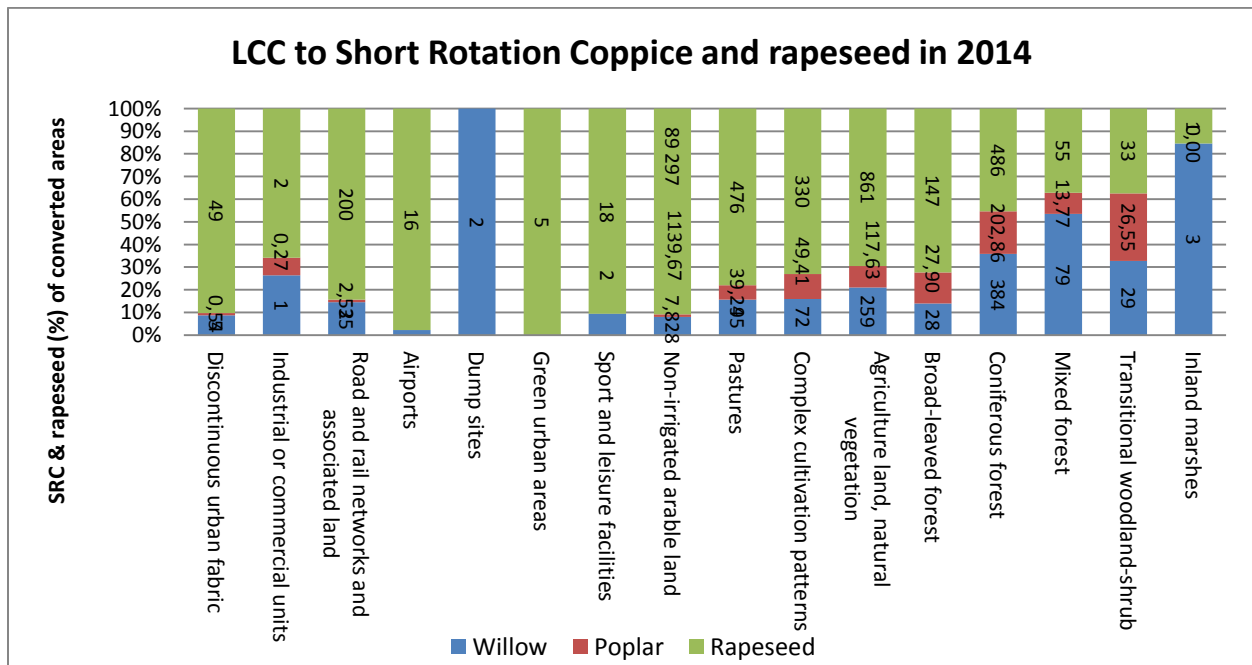


Figure 11 Areas of LCC from different land cover types to Short Rotation Coppice and rapeseed in 2014 within study area (ha) and share of SRC and rapeseed of total converted areas (%)

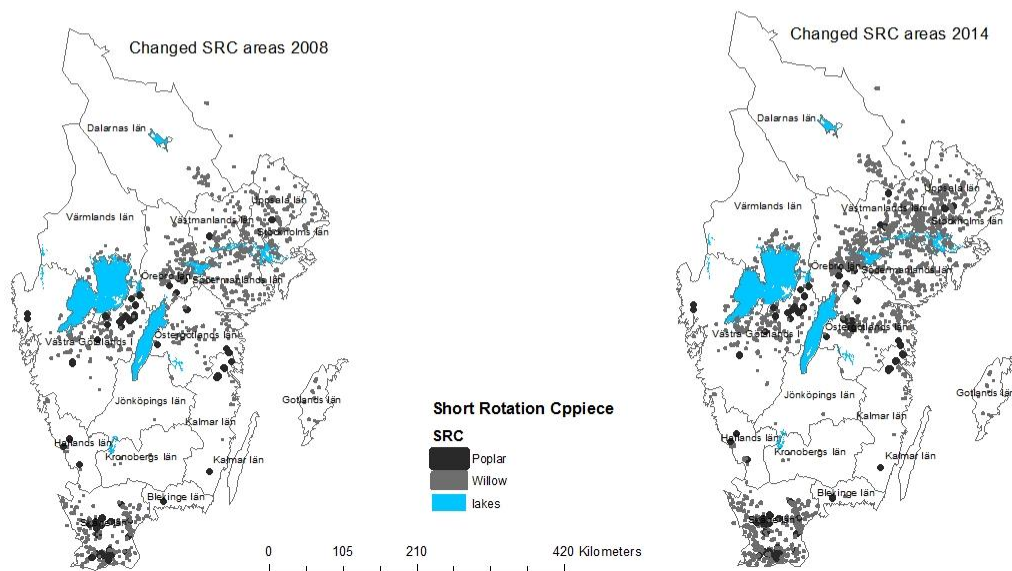
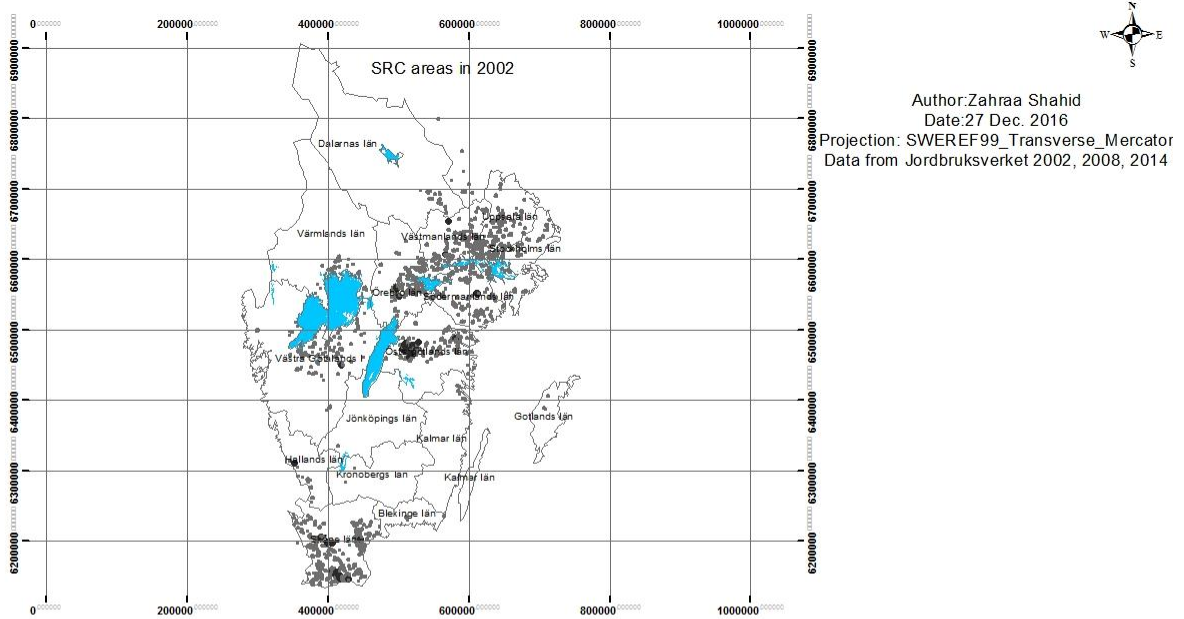


Figure 12 The changed areas of SRC are shown in three maps, geographical distribution of willow and poplar areas in 2002, increased SRC areas in 2008 and the decreased willow areas and increased poplar areas in 2014 in Svea and Götaland regions

4.4 Isoprene emissions from Short Rotation Coppice and LCC

The annual isoprene emissions from willow plantations between 2002 and 2014 are illustrated in figure 13. The estimations were based on the simplified methodology that shown in section 3.2 (figure 2), calculating monthly isoprene emissions using equations 13 and 14 of different foliar densities, depending on SLA and LAI values which were adopted from Merilo et al. (2005) case study. The standard emission rate used in this present study was $7 \mu\text{g g}^{-1} \text{h}^{-1}$. The estimations of annual isoprene emissions were shown in ton per year, since these estimations are depended on the size of planted areas. During 2005 and 2007, the fluxes were the highest in comparison to other years, such as the case in 2014 where there was only 87 tons of isoprene released from willow plantations. On the other hand, poplar (*P. trichocarpa*) plantations had relatively higher annual emissions (figure 14) since its standard emission rate was $53 \mu\text{g g}^{-1} \text{h}^{-1}$. The highest flux occurred in 2013 with 87 ton and in total there was about 164 tons of isoprene was emitted from poplar (*P. trichocarpa*) and willow (*S. viminalis*) in 2014.

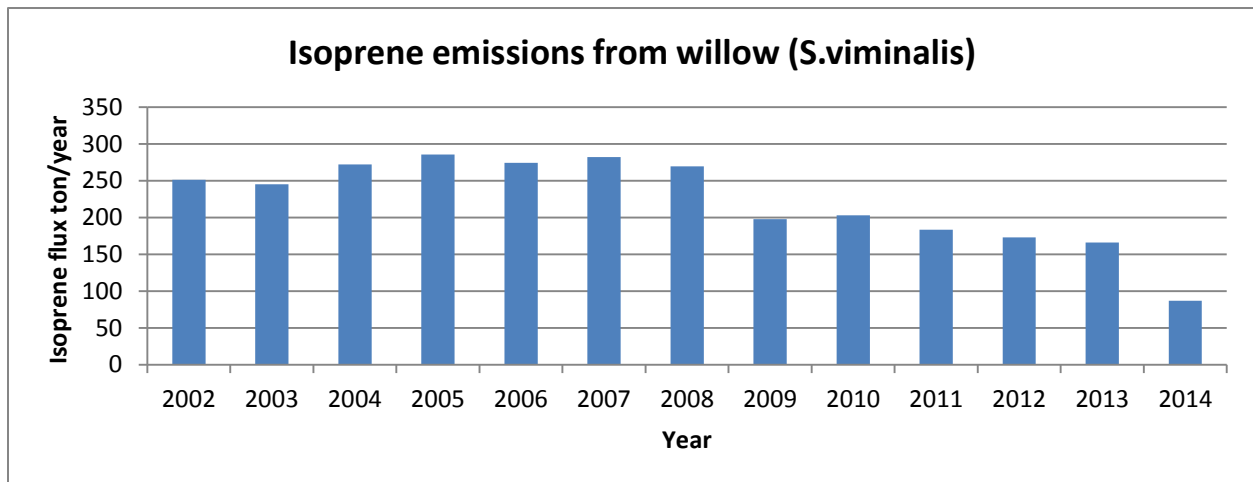


Figure 13 Annual isoprene turnovers (ton yr⁻¹) from fertilized willow (*S. viminalis*) under sunlight and shade conditions within study area between 2002 and 2014

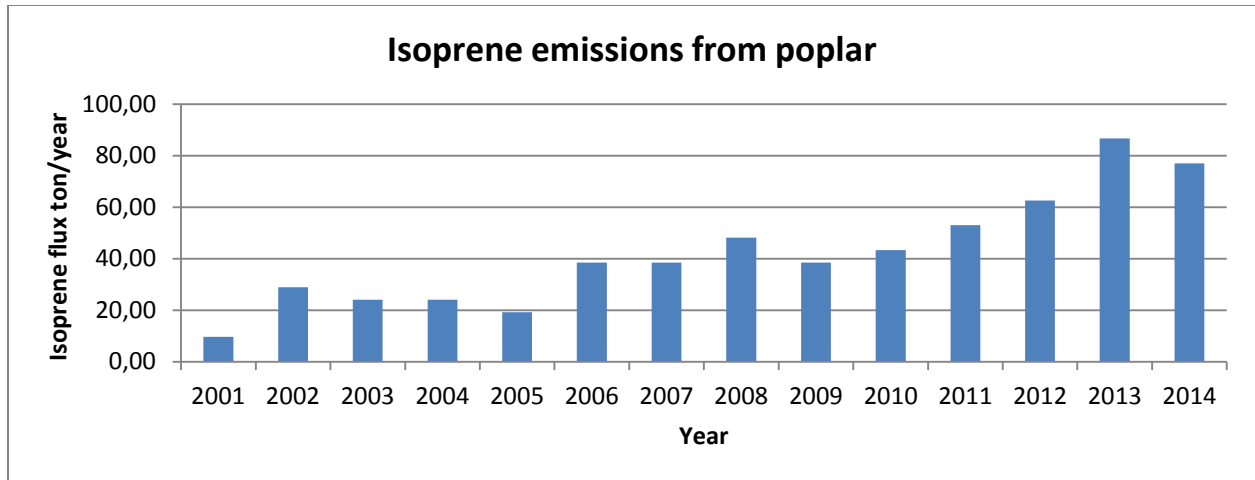


Figure 14 Annual isoprene turnovers (ton yr⁻¹) from poplar (*p. trichocarpa*) within study area between 2002 and 2014

Also, other isoprene estimations were calculated in relation to LCC from forest/agriculture land into SRC as they are shown by ton per year in figures 15 and 16B. A comparison of released isoprene from different vegetation of the same size of areas is shown in these figures. In other words, what would be the amounts of released isoprene from the unchanged vegetation into SRC compared to amounts of isoprene from changed vegetation into SRC each year.

There was about 1700 ha of forest land which had been converted into SRC in 2014 (Table 8) mostly from coniferous type of forest. The released isoprene from each forest type is presented in the first column if the changed lands have remained forest. For example there was about 1200 ha of coniferous forest had been changed into SRC, and a comparison between these three different vegetation are presented in this figure as coniferous forest would emit 15 ton for the total area (1200 ha) if the changed land has remained as coniferous, 8.5 ton and 19 ton from changed land into willow and poplar plantations respectively and in relation to each type of vegetation, the highest fluxes would come from poplar compared to coniferous, and broad leaved forest and mixed forest compared to willow and poplar. In figure 16A, the size of LCC from different agriculture land types into willow and poplar are shown. There was about 9000 ha of land used for SRC i.e. about 90% of the used agriculture land was non-irrigated arable land, with other land types were also used but relatively small areas. The estimations of annual isoprene emission from these converted agriculture lands were shown in figure 16B in ton per year. The same methodology was used for isoprene estimations using the foliar densities and standard isoprene rates from Table 1. A total of 7800 ha of non-irrigated arable land emitted only 15 ton of isoprene, while 129 tons and 15 tons were emitted from willow and poplar respectively, where both replaced non-irrigated arable land.

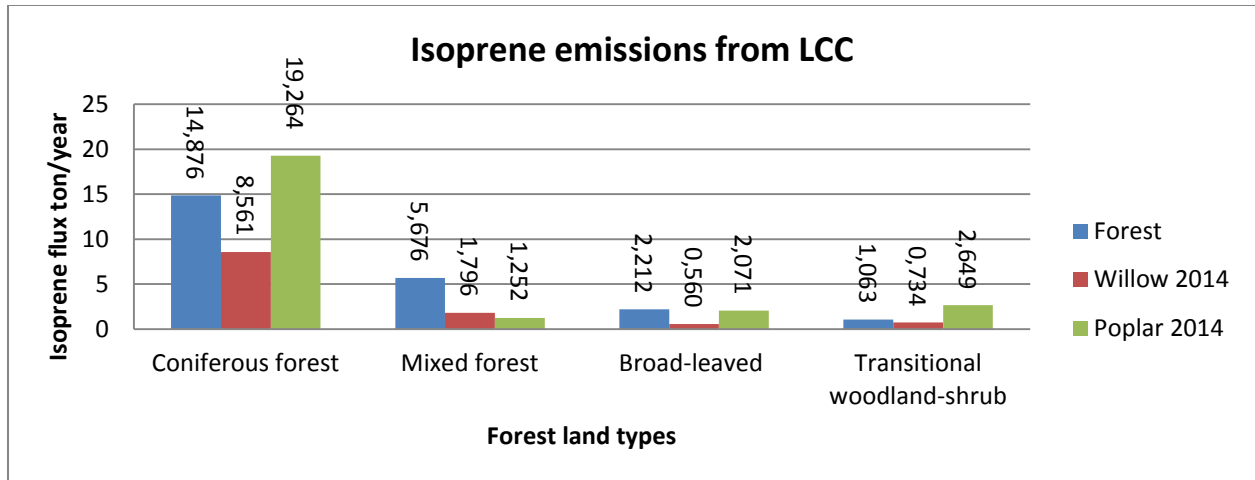


Figure 4 Annual isoprene emissions (ton yr^{-1}) from willow and poplar plantations, and from different forest types that were converted into SRC in 2014 within study area

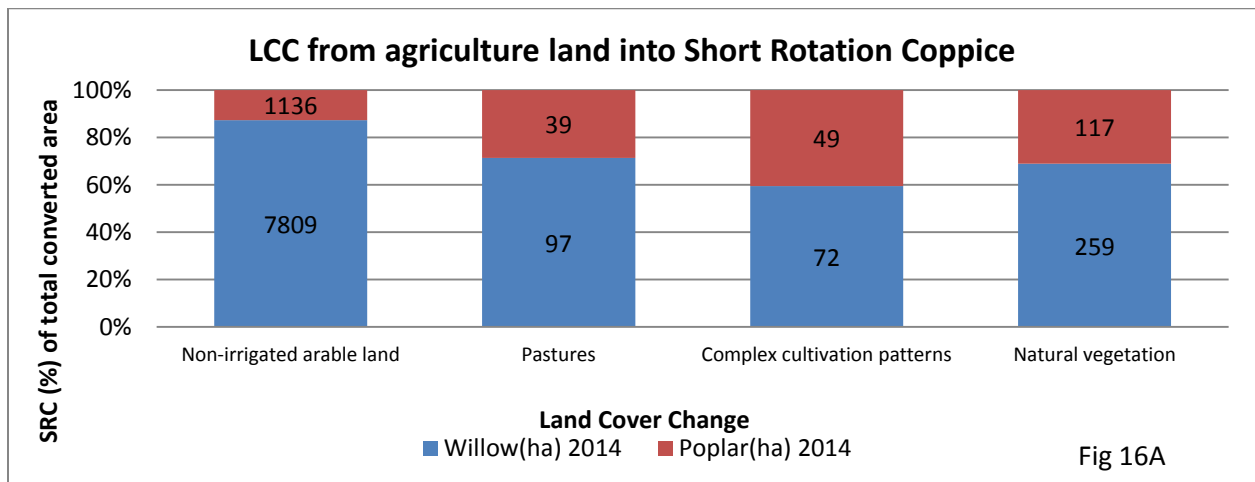


Fig 16A

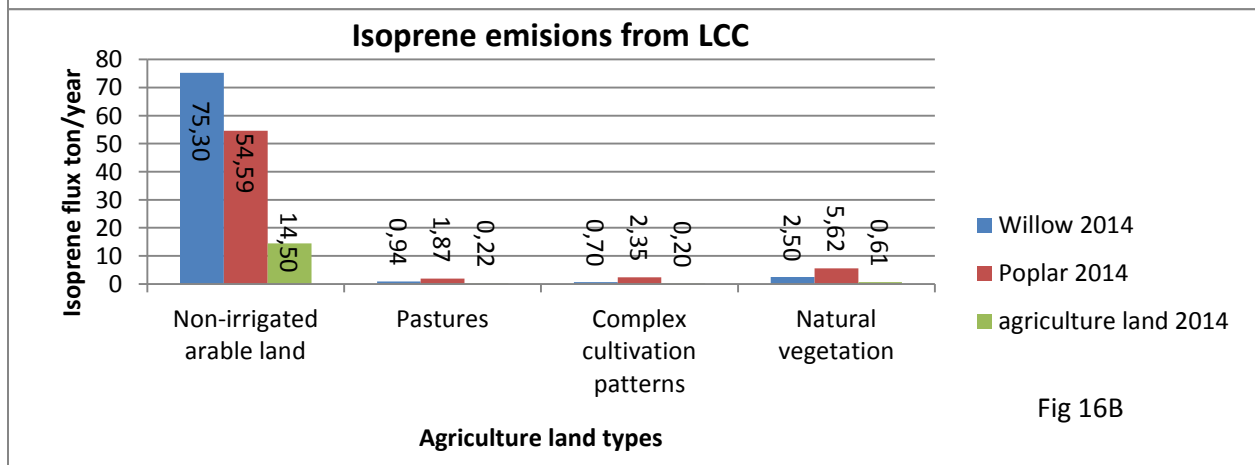


Fig 16B

Figure 16A LCC from different agriculture land types (ha) to Short Rotation Coppice in 2014 within study area, figure 16B annual isoprene emissions (ton yr^{-1}) from willow and poplar plantations, and from different agriculture land types in 2014 within study area

The annual isoprene emissions from the different land cover types were modeled as a map in figure 17, the types of land cover were chosen based on the most land cover changed into SRC. Non-irrigated arable land, coniferous forest, mixed forest and agricultural land with mostly natural vegetation were selected for analysis since those types of land cover were the largest land covers that were changed into SRC, as the above results from showed (figure 16A and table 8). Isoprene released from them was calculated by ton per km² per year.

Mixed forest was the highest emitters among other types, 2.43 ton/km²/yr. Non-irrigated arable land which is the main land used for SRC, emits only 0.15 ton/ km²/yr. Also, the annual isoprene emission from willow and poplar plantations, emitted 1 ton/ **km²** and 4 ton/ **km²** in 2014 respectively. And in comparison to emissions from non irrigated arable land, it can be seen a big difference in the released emissions between them. On the other hand, the mixed forest emits less than poplar plantations and coniferous forest emits almost the same amounts of isoprene per year. The third map in figure 17 shows a suitability land analysis was carried out considering the **NO₂** levels that less than 1.88ug/**m₃** and non-irrigated arable land in both regions, to map and illustrate the areas where non-irrigated arable land could be changed into willow along with minimizing the risk of having the chemical interaction between released isoprene and **NO₂** concentrations in these areas. The GIS analysis showed the size of these areas was about 300,000 ha with its spatial distribution as it can be seen in figure 17. These sites are distributed in areas where there are no or only few hectares of SRC plantations in comparison to the spatial distribution map in figure 11 and the share of SRC areas of total planted area in each county (figure A1) and figure 12. After carrying out suitability land analysis, the first map in figure 17 shows the scenario of emitted isoprene from these potential willow plantations that would cover about 3000, 000 ha of non-irrigated arable, they would emit 0.88 ton/ **km²** /yr distributed over Hallands, Värmland and Dalarna. Also, the quantification of annual released isoprene from total area of each land cover use is shown in figure 18 by kiloton per year in both regions. Isoprene from willow and poplar plantations forms only a small amount of the total emissions which is estimated of 0.07% of total isoprene.

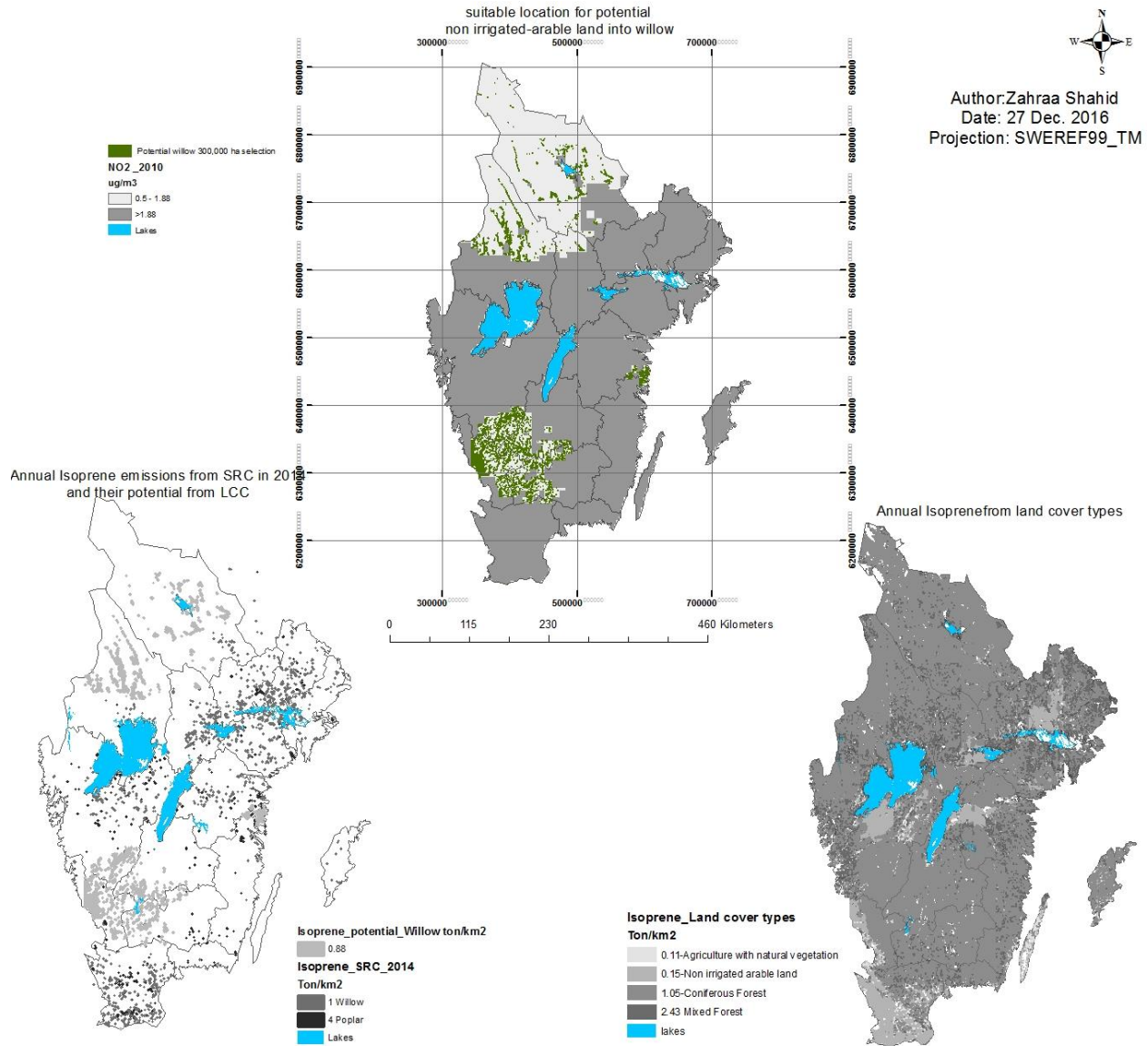


Figure 17 Annual isoprene turnovers (ton/ km²) from SRC planted area in 2014 and potential isoprene from selected non-irrigated arable land to be changed into willow using the location suitability scenario. The second map shows different values of emitted isoprene (ton/ km²) from different land cover types in Svealand and Götaland regions. The third map shows suitable locations to expand willow for biofuels using non-irrigated arable lands that can be changed into willow plantations within sites that located under less than 1.88 ug/m₃ NO₂ levels.

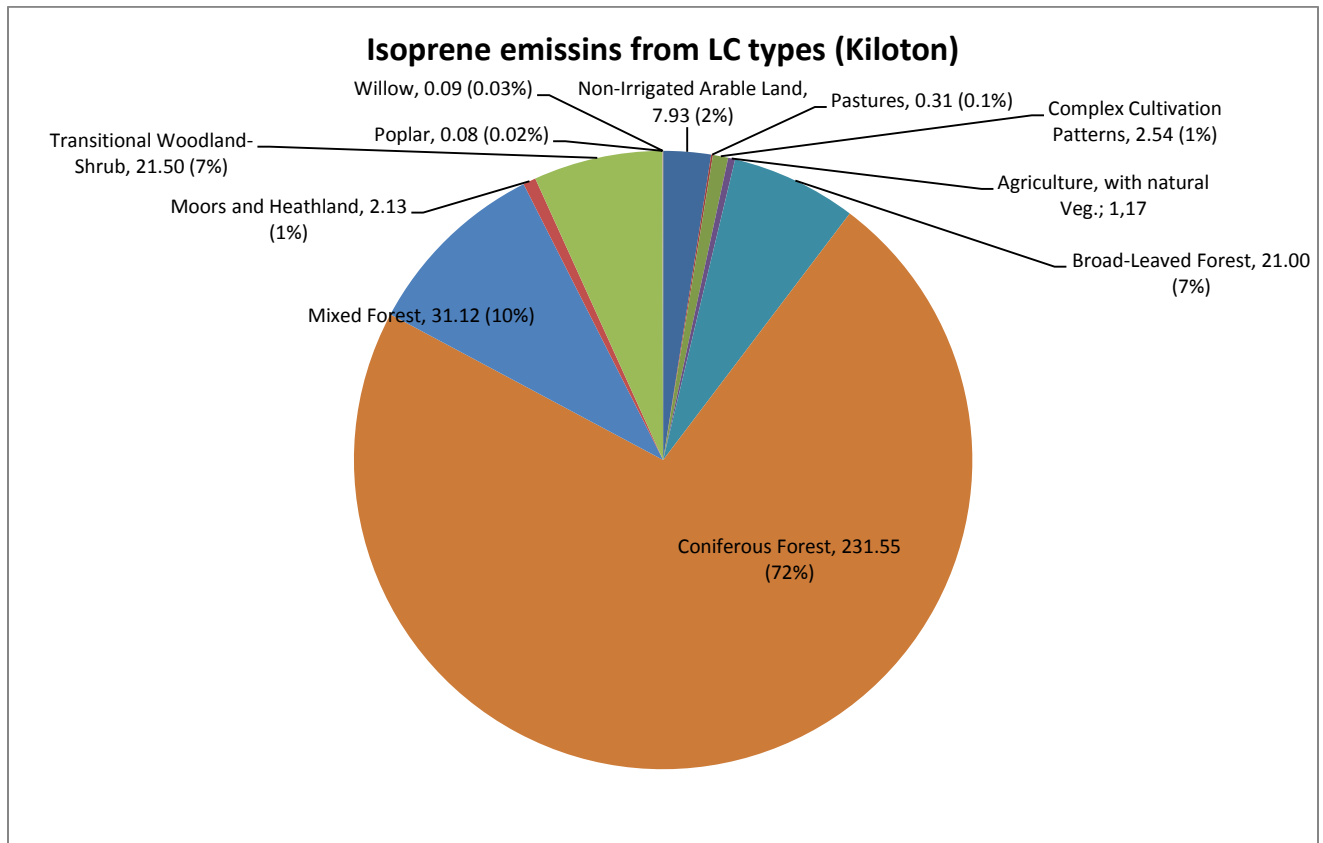


Figure 18 Annual isoprene emissions in kiloton of each land cover type area in Svealand Götaland

4.5 Harvest in biofuel energy per area

The energy characteristics of willow and poplar plantations depend on species variations. The quantity of heat produced by willow and poplar combustion is about 19.97 Megajoule per kilogram dry matter (MJ/ kgdm) and 19.43 MJ/kgdm respectively (Strömberg, 2006). The energy stored in poplar biomass is 18200MJ/kgdm with only 368 MJ/kgdm used as input energy in the lifecycle production process (Lötjönen and Laitinen, 2009). The energy efficiency is the energy production divided by energy consumption (Heller, Keoleian, and Volk, 2003) and the energy effectiveness is defined as Energy yield minus energy input.

The area used for willow plantations was about 9000 ha (figure 3A), assuming to harvest about 10odt/ha per rotation cycle, in this case a 90,000odt is the expected yield for the total cultivated willow land per rotational year in this study area. The net energy gain in a willow dried matter is

about 242.3 gigajoules (GJ) $ha^{-1} yr^{-1}$ (Stolarski et al., 2013), thus the final generated energy for the total willow used area is 2180700 GJ which equals 0.61TWh. In 2006 the estimated energy production based on willow was 0.6TWh in Sweden (SOU, 2007).

The area used for poplar plantations was about 1600 ha (figure 3A). The net energy gain in poplar after processing into bioelectricity was about 546.5 GJ $ha^{-1} yr^{-1}$ (Dillen et al., 2013), thus the final generated energy for the total poplar used area is 874400 GJ equals 0.243TWh, thus the potential total generated energy for bioelectricity from willow and poplar within this study area is estimated 0.85TWh of energy per rotational year.

Regarding rapeseed plantation and straw, the energy yield is about 220 GJ $ha^{-1} yr^{-1}$ (Börjesson, 2007). In this study, the total land used for rapeseed is about 92775 ha for autumn and spring varieties in 2014 (figure 3B), resulted in 20410500 GJ energy output for the total cultivated area per year. The direct energy input of rapeseed and straw is 30.5 GJ $ha^{-1} yr^{-1}$ including fertilizers and diesel (Börjesson, 1996), which resulted in 2829637.5 GJ energy input per year for the total cultivated area. The energy effectiveness (energy yield - energy input) is 17580862.5GJ equals 4.9TWh of energy per year for the total rapeseed land. It can be said that in case there is about similar size of areas cultivated for willow plantations, the generated energy would be 6.3TWh and the energy efficiency of biodiesel based rapeseed is 7.2.

4.6 Skåne and Västra Götaland case study

Land cover in Skåne is dominated by forest land 880,000 ha, non-irrigated arable land 603,000 ha, pasture 6500 ha and artificial surfaces 94,000 ha (figures 5, 7 and 9). The share of willow and poplar plantations is about 19% and 28% respectively of the total of each planted species in 2014. This is the largest SRC proportion within study area compared to the other counties (figure A1). There is about 6700 ha of abandoned arable land (Olofsson & Börjesson, 2016) and 21000 ha of abandoned arable land in Skåne between 1999 and 2014 (Jordbruksverket, 2014b).

The soil type in Skåne region is dominated by the Cambisol and Arenosol type of soil and both are appropriate for the SRC cultivation. On the other hand, Skåne also has a large population density and characterized by very high levels of NO_2 and PM_{10} (figure 1). Not implying that PM_{10} development in these sites (figure 1) was produced due to the chemical reaction between isoprene emissions and NO_2 but this latest research of Lin et al. (2013) emphasize the importance of SRC spatial distribution to minimize the future negative effects of this potential reaction on human health, plants and the environment. Therefore, considering the spatial distribution of the atmospheric concentrations of NO_2 is recommended since the isoprene flux from SRC are highly reactive with NO_2 which eventually lead to increased PM_{10} and O_3 air pollutants. The LCC has occurred from agriculture land into SRC in addition to small patches of other land cover types such as forest lands, pastures and urban areas. Västergötland is selected as

a potential county to expand SRC plantations since it has the land qualities and the atmospheric background that is better suited for SRC plantations to not be harmful in relation to the environmental issue of increasing O_3 and PM_{10} in the air.

Västra Götaland is dominated by forest land with about 2 600,000 ha and non-irrigated arable land of 682, 000 ha (figure 5 and 9) which is slightly more than in Skåne and could be used for SRC cultivation intensively. The share of willow and poplar was only 7% and 12% of the total SRC planted area respectively in 2014 (figure A1) mostly clustered around Vara municipality. In Västra Götaland the LCC from non-irrigated arable land into SRC was about 50% less than the LCC that had been occurred in Skåne, 700 ha and 1600 ha respectively. There is about 13000 ha of abandoned arable land (Olofsson & Börjesson, 2016) and 23000 ha of reduced arable land (Jordbruksverket, 2014b).

In general, in Västra Götaland the NO_2 levels ranged between 1.2 and $34.8\mu g/m_3$. As it is discussed in Hewitt et al. (2009), ground level O_3 increases over high isoprene emitted trees where NO_2 levels are between $1.88-18.8\mu g/m_3$. The air quality over Västra Götaland is better in terms of NO_2 levels concentrations over isoprene emitted areas. NO_2 levels between 1.88 and $18.8\mu g/m_3$ covers about 90% of the total Västra Götaland area. Also from resulted GIS statistical analysis, in Västra Götaland the isoprene fluxes from willow plantations ranged between 0 - 0.283 ton/yr which were distributed over areas with NO_2 levels between $1.7-5\mu g/m_3$.

In addition to isoprene fluxes from poplar plantations, ranges between 0.004-0.685 ton/yr were located over areas with NO_2 levels between $1.7-5.5\mu g/m_3$ which in both cases could lead to O_3 and PM_{10} formation in the region. In Skåne region, the NO_2 level ranged between 0.5 and $25.5\mu g/m_3$. Air quality in Skåne is less in terms of NO_2 concentrations over isoprene emitted areas. Statistically NO_2 levels within $1.88 - 18.8\mu g/m_3$ covered 97% of the total Skåne area. Also from GIS statistical analysis, the isoprene fluxes from willow plantations range between 0 - 0.243 ton/yr in Skåne, and were located over areas with NO_2 levels of $2.2-19\mu g/m_3$. Isoprene fluxes from poplar plantations range between 0.002- 1.511ton/yr over areas with NO_2 levels between $2-10\mu g/m_3$, in this regard and in both cases, O_3 and PM_{10} had a higher possibility to be formed. Even the availability of CHPs infrastructure in Västra Götaland seemed to be more encouraging to establish SRC plantations. There were about 15 CHP plants with production capacities ranges between 6 and 77 gigawatt hour (GWh) already established in Västra Götaland; whereas only 8 CHP plants with capacities between 7 and 90GWh could be found in Skåne (Hektor, Bruce, and Andersson, 2014). The grain production capacity also shows that the standard yield of cereals in 2014 was above average of about 7400kg/ha in Skåne, and on average about 5700kg/ha in Västra Götaland (Jordbruksverket, 2014a) which was the same as in central eastern counties. In terms of willow grower numbers, the situation was more encouraging to increase willow cultivation in Västra Götaland. For example, in Skåne region, there were

about 205 willow growers and in Västra Götaland there were about 220 growers (Rosenqvist et al., 1999).

For economic sustainability, SRC plantations supposed to be located close to CHP plants within 50-100 km distance and in proximity to roads and rails network (Guidi, Pitre and Labrecque, 2013). There is about 1700 ha and 465 ha of willow and poplar respectively in Skåne region. Proximity distance analysis to two selected CHP plants, Eslöv and Öresunds, was carried out. In order to show the share of SRC areas of total in Skåne that are located within 50km distance to those CHPs. As it is shown in figure 19, almost half of SRC plantations in Skåne are located not further than 50 km distance to Öresund CHP. And about 70% and 90% of willow and poplar plantation in Skåne are located within 50km distance to Eslöv CHP.

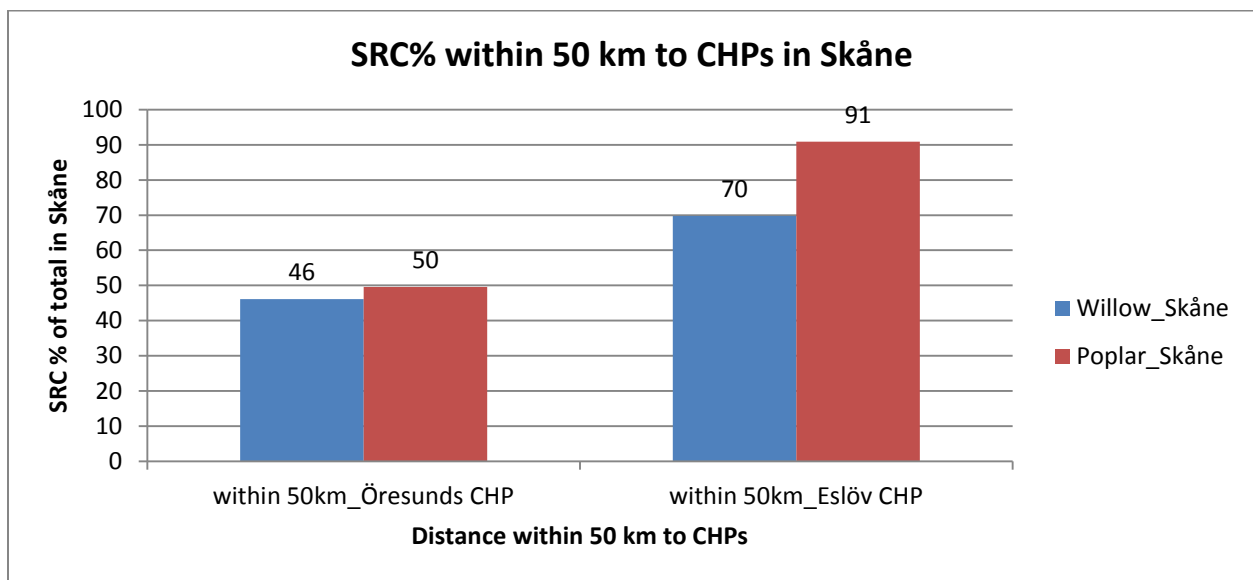


Figure 19 SRC share of total in Skåne region located within 50 Km distance to Öresunds and Eslöv CHPs

Chapter 5 Discussion

5.1 Temporal development of Short Rotation Coppice and rapeseeds

There is an increase of the areas used for SRC and rapeseed between 2002 and 2008 (figure 3A, 3B), then a decline of the areas used for willow and rapeseed (autumn and spring varieties) between 2008 and 2014, estimated by -68%, -33 % and -89% respectively (Tables 3 and 4), with one exception regarding poplar areas which have increased by 42%. Incentives were introduced to create reliable sources of energy other than fossil fuels through for climate and society. These incentives were in terms of increasing the energy taxation of CO₂ and sulphur on fossil fuels and excluding biofuels from energy and CO₂ taxes (Andersson, 2012). The price of willow pellets in Sweden was about 292 kronor per megawatt-hour (Kr/MWh) in 2012 (Dahlberg & Ekander, 2013). The government has offered subsidies to farmers who converted their lands to willow about 10,000 SEK for each cultivated ha and 360 EUR per ha for fencing (Helby, Rosenqvist & Roos, 2006).

Also from the perspective of high fuel prices impacts on the bioenergy increased demand, in Sweden in those respective years, increases in unleaded petrol (gasoline) and diesel in 2002, 2008 and 2014 have happened. In 2002 Gasoline had cost 9.19 Kronor per liter (kr/l) and diesel 7.80kr/l; in 2008 12.29kr/l and 12.09kr/l for gasoline and diesel (Fuel price reports, 2011); and in 2014 14.25kr/l and 14.82kr/l for gasoline and diesel respectively (Chart of fuel prices in Sweden, 2014). The increased areas of biofuel crops can be explained between the time period 2002 and 2008, since there is an increase in diesel and gasoline prices about 41% and 25% respectively, which corresponds to increases in SRC and rapeseed used areas.

Yet, the used areas for SRC and rapeseed showed a decline of about 68% of willow used areas and 89% of rapeseed used areas for autumn varieties, and that does not relate to the association between fossil fuels high prices and biofuels increased demands. The time period between 2008 and 2014, the increase in gasoline prices was estimated as 14% and about the same in diesel prices.

In addition, inadequate implemented weed control program played a key role in the willow areas reduction, which in some cases reduced harvest by 90% (Clay & Dixon, 1997). It is proved that it is economically inefficient to go beyond the economic threshold when the cost of weeding control methods equal to the increased yield (Cowbrough, Brown, and Tardif, 2003). Many studies suggested that cutting and seeding is the most important factors that affect the willow ability to compete weeds. Less than 100 ha of commercial willow plantations were established in

2011 due to weed control problems (Albertsson, 2012) and there have been a large number of willow plantations removed (Helby, Rosenqvist, and Roos, 2006). A survey study (Dimitriou, Rosenqvist, and Berndes, 2011) on 175 SRC growers in 2011 showed that one third of the farmers have planted willow on sandy soils, this type of lands has low potential hydrogen (pH) levels and high acid contents, which are not suitable for willow. And most of the farmers used the good quality land for other crops cultivation. They have also reported that silt and clay soils had higher yields in agreement with scientific findings (Schaff et al., 2003) regarding the appropriate soil types for willow, and 27% of the farmers terminated their SRC plantations due to lower yields than expected.

Regarding the energy and CO₂ taxes exemptions on biomass and peat, they have been always exempted since the 1990s' (Ericsson, & Werner, 2016) and still (Swedish Energy Agency, 2015). And that would have encouraged the use of SRC for biofuels, but that not the case. Since the tax exemptions did not help to sustain the already planted areas or expanding them. So there might be other reasons that discouraged the farmers to convert their land or use them for SRC plantations.

The rapeseeds have usually been used for biodiesel production for transportation and the used areas are established on former unused arable land. Concerns regarding food production competition were raised but the amount of available arable land not being used contradicts this interpretation. There is about 3 million ha of arable land, around 1 million ha are set aside or otherwise unused arable land.

A number of factors affected the decline of rapeseeds areas. The high oil prices and low biofuels prices in addition to energy and CO₂ tax exemptions led to overcompensation for biofuels producers which conflicted with the EU regulations, specifically for biofuel crops such as rapeseed since they are considered as food crops (Hektor, Bruce and Andersson, 2014). Also it was an expensive way to reduce GHG and promote the usage of biofuels according to NAO (2011). Therefore, it was decided to remove energy tax exemptions from middle of 2014 on high level blended biofuels, ethanol and biodiesel, based rapeseed and impose new energy taxes, and that supposed to have saved the budget SEK 0.6 billion per between 2014 and 2017 (OECD, 2014). And in order to get biofuels subsidies from the EU, the government enforced biodiesel tax with about 0.28 SEK per liter for low blend Fatty Acid Methyl Esters (FAME) and 0.031 SEK per kilowatt-hour (KWh) (Hektor, Bruce, and Andersson, 2014). Also, the EU Directive 2009/28/ on the use of bioenergy from renewable resources limits most of FAME feedstock, as about 75% of total feedstock must be imported from outside the EU, and only 5% were originated within from Sweden (Hektor, Bruce, and Andersson, 2014). In addition to the suspension of FAME production by small producers in 2012 and 2013, as well there are no appropriate facilities to produce FAME with low content of monoglycerides which is important for Nordic climate criteria (Grahn and Hansson, 2014).

The difference between the areas used for rapeseed and SRC is huge because rapeseed can be grown with other crops such as corn and wheat and their crop rotation fits with other crops. Also, the market for biodiesel based rapeseed in transport sector is bigger than solid biomass based SRC. In Sweden the estimated renewable energy for the transport sector forms 15.6% of the total energy used for transportation. The total production of biodiesel based rapeseed was 4.16TWh in 2014 as FAME fuel (Hållbara biodrivmedel och flytande biobränslen, 2015) which is limited up to 5% mixed with diesel oil. In addition to the transport sector, biodiesel is used for power and heat generation at small scales as an additional fuel in oil burners in small industries when it is needed (Hektor, Bruce, and Andersson, 2014). About 68% of domestic biodiesel production are in form of FAME and Hydrogenerated Vegetable Oil (HVO), with a potential to produce 18TWh in 2023 and 26TWh in 2030 (Grahn and Hansson, 2014). The two largest producers of FAME in Sweden are Perstorps BioProducts AB with production capacity as 1700GWh/year, and Energigårdarnas/Ecobränsle with 500GWh/year, currently with no full capacity production, planning to increase production capacity to 4200GWh/year (Grahn and Hansson, 2014).

On the other hand, the market for solid biomass based on SRC for bio heat and bio electricity in Sweden has lower expectation which makes farmers reluctant to dedicate their own lands to grow SRC, especially when forest residues form a strong competitor for solid biomass use in CHPs.

There is diversity in the biomass types used for heating production, but the most prominent type is forest biomass in addition to other sources such as, tree species such as birch, alder, aspen, pine, spruce, poplar and willow in form wood pellets. And for every 1TWh produced there is 217,000 tons of wood pellets have to be used. Despite the fact that the temporal development of bioelectricity production shows a positive trend, since it has increased from 3.5 to 13TWh between 2002 and 2010 and that makes it the largest source of electricity in the country, larger than the electricity based fossil fuels and other bio energy sources.

And the temporal development of bioheat shows also positive trend, from nothing in 1970s to 40TWh in 2014 (Andersson, 2012) generated in 500 bioheat plants based on wood chips across the country, some of them generating between 2 and 150GWh/yr. But still the contribution of biomass from agricultural land, such as willow is very small compared to other biomass sources, willow chips has only contributed with about 0.55 TWh into energy supply in 2013 (Statistics Sweden, 2014). Despite that there was about 17,000 ha of willow cultivated then. Also, the supply from Swedish agriculture biomass was only 2 - 3TWh for energy production in 2012; included wheat for ethanol, willow, straw and manure for biogas, with a potential to be increased to 40TWh by 2020 once willow is intensively planted on set aside arable lands (Andersson, 2012). Another study carried out by the Commission on Bioenergy from Agriculture (SOU, 2007) estimated the total potential of the Swedish agriculture biomass for energy production is 19 – 39TWh, the contribution from set-aside arable land is 5 -10TWh and land used for fodder production (pasture land) is 5-7.5TWh. That can be possible to achieve since there is 76% of total agriculture land as non-irrigated arable land in this study area (Table 5) and only 6.7% of

the total non-irrigated arable land is being used as temporary or permanent fallow according to Statistics Sweden (2013).

5.2 Short Rotation Coppice and rapeseeds plots size

In 2014, around 1550 willow plots of a total 2500 had a plot size ranges between 0.1 and 3 ha (figures 4A and 4C). 27% of willow plantation areas were composed of plots of size 3 to 6 ha and that considered the largest share of total willow planted areas, mostly distributed in southern and central eastern counties. About 50% of the willow plots in 2014 were composed of plots of size 0.1 to 6 ha as it is shown in figure 4A.

The GIS analysis results presented above confirmed the patterns of willow plot size from the Swedish Agriculture board which indicated that 42% of the willow fields are of size less than 2 ha, the average willow field size is 3.7 ha and the median is 2.5 ha (Jordbruksverket, 2008). Just about 1100 willow plots were 6 ha or even larger in 2002, compared to only 450 blocks in 2014 (figures 4A and 4C). This might be explained by the fact that; under the last 25 years non-irrigated arable land in Sweden has decreased by 275 000 ha, half of these abandoned lands were of plot size 2 ha which left unused, in addition to 100 000 ha of formerly agriculture land that are not suitable for cultivation anymore. These areas might have been used for SRC and rapeseed plantations since they are not worth to cultivate other crops which produced less than 3500 kg of grain per ha. (Jordbruksverket, 2009).

The number of willow plots that range between 6 and 10 ha size has dropped down in 2014 (figure 4C) unlike poplar plots of the same size which increased along with planted areas (figure 4D). And that might also attribute to the fact that unsuccessful SRC pre plantation planning may contribute to the low land productivity and discouraged the farmers to continue with SRC plantations despite the government efforts and subsidies for biofuels crops.

Many experts of willow plantations recommend cultivating willow on a 5 to 10 ha field size in order to have economic efficient productive yields from the used land and the harvesting machines (Larsson et al., 2007). An investigation regarding bioenergy from agriculture land shows a minimum field size of willow should be about 6 ha in order to not cross the economic threshold and that intensive cultivation would require a larger than 6 ha field size since it needs several passes on the field each year, but it is still more appropriate to keep the plot size within 6 ha for long rotation periods (Jordbruksverket, 2008). The size of plot is always associated with biomass yield and small plots would have limitations on land productivity since they are highly exposed to grazing by deer and elk, and that large area of SRC plantations would be used as headland for machine driving (Dimitriou, Rosenqvist, and Berndes, 2011). This what has been happened during the time period 1991-1996 where most of the willow field size were less than 2 ha, and the biomass yield was lower than it was anticipated (Mola-Yudego, 2009). The size of

the plot and the education level of the growers are both related to higher biomass yields (Wålstedt et al., 1992). Low productivity of willow plantations might also be a discouraging factor to dedicate larger plots for SRC. About 2000 commercial plantations in Sweden between 1989 and 2005 recorded to yield between 4 - 6.3 odt /ha/yr in the first rotation cycle and 5.4 - 7.1odt /ha/yr in the second rotation cycle (Mola-Yudego and Aronsson, 2008).

5.3 Short Rotation Coppice and LCC distribution

The increased demands for biofuels feedstock would certainly lead to direct and indirect land use change (LUC)/LCC. Multiple studies have suggested that converting croplands into energy crops had led to increased greenhouse gasses (GHG) and carbon imbalance over the years, which in return reverse the potential benefits of using biofuels (Fargione et al., 2008). Yet under the current situation LCC in terms of changing tropical land into biofuel crops has led to net carbon emissions (Gibbs et al., 2008) whereas changing cultivated cropland or degraded land would have immediate carbon savings. Concerns regarding rising food prices as a result of indirect LCC when changing croplands into energy crops have been addressed by the IPCC (2007) and the International Energy Agency (IEA) (2006). The results of this present study show that most LCC occurred from non-irrigated land into SRC plantations (Table 6) and not from forest land or other land types (Table 8), this pattern of LCC has not changed from 2002 to 2014 in Svealand and Götaland regions. The share of willow plantations of total planted areas on non-irrigated arable land was about 94% in 2002 in this study area. In 2008, it was slightly reduced to 93.5%. While in 2014, only 67% of total willow plantations and 43% of total poplar plantations grown on non-irrigated arable land (figure 6).

As shown in figure 10 and figure 11, non-irrigated arable land was the largest land cover type used for SRC and for rapeseed in 2002 and in 2014, with a total changed area into SRC (24,000 ha) and into rapeseed (112,000 ha) in 2002. Other types of land cover have also changed into SRC but on a smaller scale. The LCC in 2014 had almost the same patterns of the types of converted land but in smaller areas. Non-irrigated arable land was also the largest land cover type that was converted into SRC and rapeseeds but the size of the converted land was less than it was in 2002. Only 9,000 ha has changed into SRC which forms about 9% of the total converted non-irrigated arable land into SRC and rapeseeds. There was also about 89,000ha of non-irrigated arable land converted into rapeseeds representing 91% of the total non-irrigated arable converted land. The spatial patterns of SRC over the 12 year period (figure 12) revealed that most of them were located in south Skåne and central eastern counties of Sweden, specifically the area surrounding Hjälmarren and Mälaren lakes.

The abandoned arable land identified by Olofsson & Börjesson (2016) was about 88,000 ha of which defined as a previously cultivated and then been left out and now are suitable for cultivation, and this definition has excluded CLC change and afforestation. About 65% of these

abandoned areas were composed of plot size larger than 1 ha, and 10% of them were located on plots of size larger than 5 ha. Västra Götaland had the largest share of abandoned arable land of about 13000 ha and that forms 15% of total abandoned arable land in the county followed by Skåne and Värmland counties 6700 ha and 5700 ha, respectively, which all together contributed into 29% of the total abandoned arable area identified in Sweden. Also the Jordbruksverket statistics (2014b) identified that there was about 150, 000 ha of reduced arable land between 1999 and 2014.

Regarding the spatial distribution of SRC plots on certain cover land types and in certain counties as it is shown from GIS results, can be explained from the perspective of that these areas have average and above average grains productivity, as farmers prefer to cultivate SRC on a high yield grain farm land (Rosenqvist et al., 1997). Statistics of standard yield grains in Sweden for 2014 (Jordbruksverket, 2014a) showed that the production capacity of grains in the areas surrounding Hjälmaren and Mälaren has an average grain yield and the areas in Skåne had above the average yield. The GIS results showed that the lowest percentage of the total planted SRC plantations were in the south- eastern counties such as Gotland, Blekinge and Kronobergs and these counties have below the average grain yield production capacity and also have large pasture land (figure 7) which is mainly used for fodder production. For instance, in Blekinge, willow contribution in energy production was only 1,5GWh per year with a potential to be increased from 50 to 140GWh per year only if there will be about 3000 ha of non-irrigated arable land cultivated with willow (Gustafsson, Uppsäll, and Wälitalo, 2014).

Willow and poplar contribution into energy production was estimated to reach 40MWh per ha per year in Skåne and Hallands region (SOU, 2007), and in general there is a need to have 1000 ha of willow plantations in order to supply 9000 inhabitants with heating (Bioenergi & kretslopp stad/land, 2000). On the other hand, for example in the UK the estimated areas used for willow and poplar plantations has dropped 50% between 2008 and 2014, estimated 6200 ha and only 2800 ha respectively, with mostly established under subsidies scheme between 2000 and 2014, about 2600 ha supplied power stations with about 15,000odt in 2011. (Area of crops grown for Bioenergy in England and the UK, 2013)

Willow plantations were mainly concentrated in Skåne, Örebro, Södermanland and Uppsala counties, where they formed 65% of the total willow planted areas across this study area as GIS results showed (figure A1). This was also associated with a high number of willow growers per county; 205, 220, 108, 163 respectively (Rosenqvist et al., 1999). 80 % of total poplar plantations are mostly scattered in Skåne and Västmanlands, Västra Götaland, Södermanland and Östergötlands, as had been shown in figure 12 and figure A1.

In Kalmar, Blekinge and Gotland regions, the production cost for willow was the lowest among other energy crops such as rapeseeds and others, it had cost only 160kr/MWh compared to 425kr/MWh for rapeseed in 2008 depending on crop yields and the size of the fields

(Energimyndigheten, 2008), but still in the southern and central Sweden, willow has the lowest production costs (Jordbruksverket, 2008).

Furthermore, the suitable conditions regarding soil types in these counties might explain why these sites were selected for SRC plantations. Soils type is considered as an important determinant for the long term growth of willow (Tahvanainen and Rytönen, 1999). It has been demonstrated by experiments that sandy, clay and silt soils are most appropriate for willow and poplar (Schaff et al., 2003) and the characteristics of agricultural land has suitable traits for SRC cultivation. Soil moisture is also one of the most important factors to determine land selection; many field studies showed that SRC using 50% of water yield (Hall et al., 1996). Therefore, it is recommended that soil pH for the poplar ranges between 5.5- 7.5 (Commission and Jobling, 1990) and for willow between 5.5 -7 (Tubby and Armstrong, 2002).

From the perspective of soil type suitability in the study area, the western part of Götaland region is covered by the histosolos type of soil, which is classified by Food and Agriculture Organization (FAO) as an organic soil with low fertility and difficult to cultivate but when they are formed on glacial land they can be very productive such as in Västra Götaland where 12% of total poplar plantations are cultivated (figure A1). The Arensolo type of soil also covers large parts of southeastern and the eastern part of Götaland region (Greve et al., 1998), they are coarse textured sandy soils covering large areas of Örebro and Skåne where 34% of willow plantations are cultivated (figure A1).

On the other hand, the areas surrounding Storsjön in Jämtland and south-eastern Skåne on the Östgöta and Västgöta plains, where the largest acreage of willow and poplar are cultivated has Cambisolos type of soil. This is a silt and clay rich type of soil and covers more than 50% of the north-western part (Greve et al., 1998) of Sweden. This type of soil also covers most of the total land in Örebro surrounding Hjälmarén and Mälaren lakes west of Stockholm, where about 1500 ha of willow was cultivated in 2014. Cambisolos also covers almost all the land of Västmanlands where 15% of the total poplars are cultivated (figure A1).

About 14% of the total poplar plantations were cultivated in Östergötlands (figure A1) where Leptosolo are dominating on coastal areas in the eastern part of Östergötlands, they are featured as shallow soils over continuous rock and are considered the best suited soil type for poplar plantations (Charlton et al., 2007).

From the fuel demands perspective, the high population density in these counties (figure 1) where SRC are concentrated lead to higher fuel demands and the availability of CHP plant infrastructure could be a reasonable explanation to why SRC cultivation is clustered in these areas.

Regarding the favorability of using other agriculture land types for SRC, it was shown that pasture land was neglected (figure 7 and 8). A quantitative (Rosenqvist et al., 1999) study about willow farmers in southern and central - eastern Sweden, showed that willow was less commonly grown on pasture since most of the land was needed to feed animals. It was also reported that

non-irrigated arable lands were often used for cereal production in addition to animal fodder production.

Regarding the neglected counties that have had the lowest percentages of total SRC plantations as the GIS results showed they were in the south-eastern parts of Sweden; Jönköping, Kalmar, Blekinge, Kronoberg and Halland (figure A1). These counties have the lowest number of willow growers among the other counties within this study area, 2, 7, 2, 0 and 19 respectively (Rosenqvist et al., 1999), and have had the lowest share of total arable land (figure 5) and are mostly dominated by forest land (figure 9).

Also, biomass based wood fuel in these counties might explain why SRC are neglected in these areas. In 2014, the total supply of forest biomass for biofuels was about 75TWh and 150TWh once all forest biomass had been used for energy purposes, with a potential to rise to 129TWh by 2020, and it is expected to have 50 million m₃ as surplus in the Swedish forestry (Hektor, Bruce, and Andersson, 2014) by 2050 which indicate the sufficient energy supply from forest fuels, hence the need for energy crops is decreased. Wood products such as refined wood and black liquor have a potential to contribute to about 179TWh in the energy production (Hagström, 2006).

The south-eastern part of Sweden is considered the largest region in the country that contributes to the energy forestry (Hammar, 2015). The annual estimated forest biomass production is about 76 Gt Megaton (Hektor, Bruce, and Andersson, 2014) which comes from different sources, forest residues have big potential to be used for biofuels since only 70,000 ha of total 200,000 ha per year is being harvested as forest residuals. For example a case study of three locations in Sweden estimated yields from logging residues to be 48 tdm/ha with a rotation period every 70 years in Jönköping, 35.3 tdm/ha in Dalarna with a rotation period every 90 years and 33.5 tdm/ha in Västerbotten with a rotation period every 120 years (Hammar, 2015). The low population density in the south-eastern areas compared to the south and central eastern counties as it was shown by the population density map (figure 1) is also an indicator that there would be less demand for fuels in these counties.

5.4 Isoprene emissions and NO₂ atmospheric background

The estimations of annual isoprene fluxes in this study (figures 13 and 14) were based on parameters of LAI and SLA characteristics of the willow (*S. viminalis*) adopted from Merilo et al., (2005) case study and shown in Table 2, which investigated leaf photosynthetic properties in willow (*S. viminalis*) and other species. The standard emission factor used for willow (*S.viminalis*) was based on canopy-scale method from Olofsson et al. (2005) case study. In this present study applying to these parameters to estimate annual isoprene from willow resulted in about 87 ton per year of isoprene emitted from the total area used for willow in 2014 (figure 13) and 77 ton of isoprene emitted from poplar used areas (figure 14), where both plantations have

only covered 0.3% of the total non-irrigated arable land in this study area. On the other hand, these results assumed that the total area were planted with willow (*S. viminalis*) species, so in case that there are other types of willow species were used, the results of these estimations would be higher since the standard emission rate of isoprene is higher, like willow (*S. phyllicifolia*) that were chosen in Mozaffar's study (2013). For instance the standardized isoprene emission potential was $56.4\mu\text{gg}^{-1}\text{h}^{-1}$ which was about 8 times higher than willow (*S. viminalis*).

In Sweden there are about 20 million ha of coniferous forest which forms 80% of total forest land in Sweden (Table 7), the total area of coniferous forest were the largest isoprene emitting sources in study area which formed about 73% of the total isoprene emissions and that's about 231 kiloton per year at $3\mu\text{gg}^{-1}\text{h}^{-1}$ standard emission rate (figure 18). In addition, broad-leaved forest and mixed forest released about 10% of the total emitted isoprene in Sweden, and globally annual isoprene emissions were about 500,000 kiloton per year from different vegetation (Arneeth et al., 2008). The total non-irrigated arable land has emitted only 2% of the total isoprene emissions and that's about 8 kiloton (figure 18) covering 6.6% of the total land area. Willow emitted less amounts of isoprene when replaced certain forest lands, in contrast to poplar plantations, which released larger amounts of isoprene annually when replaced different types of forest land except mixed forest (figure 15). In 2014, about 14.6 tons of isoprene was released from willow plantations planted on 890 ha of coniferous forest and 19 tons of isoprene from poplar that covered only 400 ha of forest land. Although, the NO_2 concentrations had low levels in the counties where forest areas are mostly dominated (figure 1) but these areas have peaty soils Histosol type of soil which is very difficult to establish SRC plantations on them. However, a clear-cutting fertile land used for old forest can be used for SRC plantations (Skogsstyrelsen, 2008) in temperate climate zones such as south and south eastern parts of Sweden.

The isoprene released due to LCC from agriculture land into SRC was about 137 tons and only 15 tons of isoprene would have been emitted directly from different agriculture land types (figure 16 B) of the same used areas. A scenario to replace 72 million ha of set-aside land and pasture land to cultivate willow and poplar in Europe would increase isoprene by 4500 kiloton and that would lead to a 6 parts per billion by volume (ppbv) of mean O_3 by month and 0.8 ppbv by year above the SRC heavily planted areas on a regional scale, and 6 ppbv on local scale such in eastern Europe (Ashworth, Wild, and Hewitt, 2013).

The NO_2 concentrations over this study area ranges between 0.5 and $30\mu\text{g}/\text{m}_3$ and the highest level of NO_2 happens to be in the southern and central eastern counties (figure 1). However, NO_2 levels over the isoprene emitted areas from willow were between 1.4 and $19\mu\text{g}/\text{m}_3$ where willow released about 1 ton/ km^2 in 2014; and NO_2 levels over the isoprene emitted areas from poplar were between 1.2 and $10\mu\text{g}/\text{m}_3$ where poplar released about 4ton/ km^2 in 2014 (figure 17). The scenario of potential willow plantations for expansion would change 300, 000 ha of non-irrigated arable land into willow. It showed the isoprene emissions per year would be about 0.88 ton/ km^2/yr and that would contribute to about 2.6 kiloton of isoprene each year from the total

planted area. Where the unchanged non-irrigated arable land would release 0.15 ton/km²/yr, and that release only 450 ton of the total 300,000ha area. The mixed forest release the highest amount of isoprene, it is understood that forest land would be expensive to convert into SRC. So forest lands would be unrealistic option to replace and expand SRC for biofuels and therefore selecting unused arable lands under certain conditions is more viable. Also in figure 17, the released isoprene were shown from other different land uses by ton/km² per year, such as forest lands and agriculture lands. The spatial distribution of isoprene from mixed forest had the highest in Uppsala and Stockholm and Västra Götaland.

Several studies showed that at certain levels of NO₂ and isoprene increases in O₃ is likely to happen. Isoprene emissions increased by 3.5 kiloton per year due to LCC from agriculture land into SRC which led to monthly increases in O₃ level by 0.7ppbv (Hardacre et al., 2012). And that NO₂ levels between 1.88 and 18.8 µg/m₃ could affect air quality largely at any increases in isoprene emissions (Porter, 2013). In this study we considered this assumption that isoprene emissions under this NO₂ level would lead to O₃ formation and to avoid the risk for chemical interactions NO₂ has to be 1.88 µg/m₃ or less, since the chemical interaction is NO₂ controlled (Olofsson et al., 2005). Also, a study about Giant Reed plantation that has standard emission rate as 34 µg g⁻¹ h⁻¹ where NO₂ was at 64 µg/m₃ and VOC levels at 3.1ppbv has showed that any additional of isoprene would increase in peak 8-hour O₃, i.e. from 2.7 to 14ppbv (Porter, 2013). Another case study of oil palm trees that has isoprene emission standard rate at 8 ug/g/h had chemical reaction with NO₂ concentrations between 5.548µg/m₃ and 9.247µg/m₃, the reaction produced 100ppbv of O₃ (Hewitt et al., 2009). According to the World Health Organization (WHO) exceeding 50ppbv of O₃ would affect air quality and 124ppbv would be extremely dangerous.

The GIS analysis showed that about 98% of the total willow plantations and 90% of total poplar were located in sites under NO₂ concentrations between 1.88 and 17µg/m₃ (1-10ppbv) (figure A2 in Appendix). These sites have high population density, particularly, in central- eastern and southern areas (figure 1) where SRC is most cultivated (figure 12) and that need to be reconsider in the future after carrying out a chemical transport model to investigate the interaction between isoprene and NO₂ levels in these sites and how much that can be contributed to O₃ formation.

Suitability location analysis of potential SRC areas in low NO₂ levels regions shown in figure 17, might be a good solution to expand SRC plantations without having impacts on air quality. Since in low NO₂ and high isoprene level areas, O₃ increases with increasing NO₂, and in this region O₃ production is NO₂ controlled, and increases in isoprene emissions will have no or little impacts on O₃ production. (Sillman,1999). On the other hand, NO₂ levels are low in these areas, less than 1.88 ug/m³, and they are unlikely to increase, due to its less populated areas as is shown in figure 1. And isoprene that can be released in such scenario would be about 2.6 kiloton per year (0.88 ton/km²) for the total covered area (figure 17), and at any increase in isoprene levels the chemical interaction between isoprene and NO₂ can take place when NO₂

ranges between 1.88 and 18.8 $\mu\text{g}/\text{m}_3$ (Porter, 2013), in this case these suitable areas can be recommended for SRC plantations expansion in the future.

While in high NO_2 levels and low isoprene levels, O_3 decreases with increasing NO_2 and it increases with increasing isoprene (Sillman, 1999). Such as the current situation, any expansion to SRC plantations in the current locations would probably have impacts on air quality in terms of O_3 increases.

There are a number of similar studies related to this present study from the perspective of having the same purpose to quantify LCC and isoprene emissions using different methods. All The results of the literature studied are suggesting that SRC would have consequences on air quality but the quantification of isoprene was on regional level so it would be difficult to draw comparison regarding the results. With one exception, Olofsson et al. (2005) study suggested that isoprene fluxes in Sweden have shown no major impacts on the local air quality since the dispersion process was faster than the chemical reaction with NO_2 to form O_3 , but this is a subject to change once the atmospheric mixing is controlled under a stratified surface layer, even the sensitivity analysis that was carried out for NO_2 and VOC has shown that O_3 formation was NO_2 controlled.

5.5 Harvest in biofuel energy per area

The energy efficiency of willow and poplar is always larger than rapeseed and other energy crops such as wheat and maize. For example poplar, willow and rapeseed have 34:1, 21:1 and 5.9:1 units of energy respectively (Börjesson, 2007). Biodiesel based on rapeseed would have 5.9 units of energy for 1 unit of fossil energy that is consumed over rapeseed lifecycle. On the other hand, fossil fuel diesel's life cycle produced only about 0.84 units of energy per 1 unit of fossil energy consumed (Pradhan et al., 2009), Yet, within this study area the energy efficiency of rapeseeds were 7.2 units of energy.

According to the results presented in section (4.5) the final generated energy for the total willow and poplar used area were about 0.606TWh and 0.243TWh respectively per rotational year. The statistics of the Swedish energy production based willow plantation in 2005 is estimated 0.6TWh (SOU, 2007).

There is about 600-700,000 ha of abandoned land in Sweden, 100,000 ha of that areas were used for afforestation according Swedish agriculture board (Jordbruksverket, 2008). Also, 300-500,000 ha of productive agricultural land is already available (Kommissionen mot oljeberoende, 2006) at which could SRC be planted. A total 300,000 ha of willow is needed to be planted in Sweden to produce 20TWh of energy. However, a scenario of increasing the area used for willow to 223, 000 ha in 2020 showed to produce 10.5TWh (SOU, 2007).

The location suitability analysis in this study was carried out to show the available non-irrigated arable land in sites where NO_2 levels are at $1.88\mu\text{g}/\text{m}_3$ threshold. There is about 4,600,759 ha of non-irrigated arable land that were located in sites where NO_2 are between 1.88 and $18.8\mu\text{g}/\text{m}_3$ and about 300,000 ha were located in sites where NO_2 levels less than $1.88\mu\text{g}/\text{m}_3$ (6.5% of total non-irrigated arable land area). And in order to minimize the risk of the interaction between emitted isoprene and NO_2 , the 300,000 ha could be suitable to plant willow and poplar plantations. These areas of non-irrigated arable land can be converted into willow and contribute to about 20TWh of energy, which are mostly located in Hallands, Kronobergs, Värmlans, Dalarna, south eastern Jonköping, south-east Östergötland and south of Västra Götaland (figure 17) and these counties there were very few hectares of land were dedicated for SRC plantations.

Chapter 6 Conclusion

Sweden has already met the European target set by 2020 years ago to have 20% of the total energy production supplied from renewable energy sources; in fact 50.6% of the total energy use in the country now comes from renewable energy and bioenergy has 33.6% share of that contribution. So in that respect, the country objective must be to go 100% fossil fuels free in the coming years. The question is to what extent SRC for biofuels would contribute into that objective without having reverse impacts on air quality.

The results did not support the assumptions set in the beginning regarding the temporal development of increased biofuels areas over 12 years period, i.e. the areas used for SRC had increased between the time period 2002 and 2014 to meet the energy demands.

Actually, the areas used for SRC and rapeseed plantations in the Svealand and Götaland region showed an increase between 2002 and 2008 and then a rapid decline between 2008 and 2014 of -68% of total willow planted area, -33 % and -89% of the total rapeseed planted areas for autumn and spring varieties respectively, with one exception, poplar areas have increased by 42% by 2014.

GIS results also show an increase in the number of small plots that are equal or less than 6 ha and the removal of large plots that were existed between 2002 and 2008. Most of the SRC plots are composed of plots that had less than 6 ha in 2014 forms about 50% of total willow plots. The results also show that the energy value of SRC for the first rotation cycle was estimated to provide 0.85TWh for the 9000 ha, while the energy value of rapeseed and straw is 4.9TWh for the 90,000 ha cultivated land. However the energy efficiency and effectiveness of SRC are more than other crops in a way that it can increase bioelectricity and bioheating energy production from 0.8 to 20TWh based on agriculture land, once 300,000 ha of suitable non-irrigated arable land is used for willow.

The areas used for rapeseed were larger than the areas used for SRC. The percentage of the LCC from agricultural land into rapeseeds was many times more than LCC from agricultural land into SRC, and that was associated with an increase number of rapeseed plots, about 51% of the total plots number composed of plots which were equal or less than 6 ha in area. The results supported the hypothesis that LCC was basically happened from non-irrigated arable land into SRC and rapeseeds crops. In 2002 the share of willow plantations of total non-irrigated arable land was 0.5%. The converted areas from non-irrigated arable land into SRC has increased in 2008 and then decreased in 2014. On the other hand, forest lands were not favorable sites to be converted to willow. In 2002, only 12% of the total willow plantations were planted on forest land, but in 2014 this increased to 20% of total planted willow. About 82% and 95% of the total changed arable land were dedicated to rapeseeds in 2002 and in 2014 respectively.

The results supported the hypothesis III that the quantities of released isoprene fluxes from willow plantations are located in sites where NO_2 levels might be sufficient for a chemical reaction with isoprene and eventually could lead to O_3 . However, there was about 75 tons of isoprene was estimated to had been released from a 7800 ha of willow plantations and only 15 tons would have been emitted from the same size of non-irrigated arable land areas and about 55 ton had been emitted from a 1000 ha of poplar covered areas that has replaced the non-irrigated arable. These results indicate that the emitted isoprene from SRC is 9 times more than released from agricultural crops.

Willow and poplar for biofuels is a fairly small contributor to the bioenergy sector in Sweden with a reduced size of areas between 2002 and 2014. From this model, we can better understand that isoprene released from SRC plantations is only 0.05% of the total emitted isoprene in Sweden.

The potential suitable sites were estimated to be 300,000 ha, although that would increase the levels of annual released isoprene from SRC from 0.03% 1% of the total isoprene emissions but it would contribute to 29TWh.

The results of the comparison between Skåne and Västra Götaland in the light of isoprene fluxes under certain NO_2 levels, and the land resources that are available and suitable for SRC cultivation in terms of non-irrigated arable land and appropriate soils would support the recommendation that Västra Götaland region needs to be considered in the decision making process to expand SRC cultivation for biofuels production.

The contribution of this study could support the decision making process about the selection of SRC locations in the context of LCC from agriculture land and other land cover types, and in the context of the NO_2 to avoid or reduce the impacts of LCC into SRC on air quality in Sweden. Furthermore, a transport and chemistry model needs to be implemented in the future to analyze the effects of the current SRC plantations estimations results (spatially and temporally) on air quality in terms of O_3 and PM_{10} production in Sweden.

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Appendix A

Table A1 CORINE land cover data levels and classes (SMD, 2015), the first level has main five classes of main land cover types on the planet, the second level is used to project on a scale of 1:500 000 and 1: 1 000 000 which has 15 classes, and the third has 44 classes used to project on a scale of 1: 100 000

| Vegetation class code | CORINE land cover level 1 | CORINE land cover level 2 | CORINE land cover level 3 |
|-----------------------|-------------------------------|---|--|
| 112 | Artificial surfaces | Urban fabric | Discontinuous urban fabric |
| 121 | Artificial surfaces | Industrial, commercial and transport units | Industrial or commercial units |
| 122 | Artificial surfaces | Industrial, commercial and transport units | Road and rail networks and associated land |
| 124 | Artificial surfaces | Industrial, commercial and transport units | Airports |
| 131 | Artificial surfaces | Mine, dump and construction sites | Mineral extraction sites |
| 132 | Artificial surfaces | Mine, dump and construction sites | Dump sites |
| | | | |
| 141 | Artificial surfaces | Artificial, non-agricultural vegetated areas | Green urban areas |
| 142 | Artificial surfaces | Artificial, non-agricultural vegetated areas | Sport and leisure facilities |
| 211 | Agricultural areas | Arable land | Non-irrigated arable land |
| 231 | Agricultural areas | Pastures | Pastures |
| 242 | Agricultural areas | Heterogeneous agricultural areas | Complex cultivation patterns |
| 243 | Agricultural areas | Heterogeneous agricultural areas | Land principally occupied by agriculture, with significant areas of natural vegetation |
| 311 | Forest and semi natural areas | Forests | Broad-leaved forest |
| 312 | Forest and semi natural areas | Forests | Coniferous forest |
| 313 | Forest and semi natural areas | Forests | Mixed forest |
| 324 | Forest and semi natural areas | Scrub and/or herbaceous vegetation associations | Transitional woodland-shrub |
| 411 | Wetlands | Inland wetlands | Inland marshes |
| 412 | Wetlands | Inland wetlands | Peat bogs |
| 421 | Wetlands | Maritime wetlands | Salt marshes |
| 422 | Wetlands | Maritime wetlands | Salines |
| 423 | Wetlands | Maritime wetlands | Intertidal flats |
| 511 | Water bodies | Inland waters | Water courses |
| 512 | Water bodies | Inland waters | Water bodies |
| 133 | Artificial surfaces | Mine, dump and | Construction sites |

| | | | |
|-----|-------------------------------|---|-----------------------------------|
| | | construction sites | |
| 222 | Agricultural areas | Permanent crops | Fruit trees and berry plantations |
| 321 | Forest and semi natural areas | Scrub and/or herbaceous vegetation associations | Natural grasslands |

In the following tables (Table A2 to Table A7), the plots of willow and poplar are classified according to size classes adopted from (Jordbruksverket, 2008). In addition to, the number of each crop plots within each size class is estimated and the areas that cover each class (hectares) are shown for the 2002, 2008 and 2014 time period. Also, the share of willow and poplar plantation that belongs to each class of total planted area is estimated.

Table A2 Number of willow parcels and size distribution in 2002 within study area

| 2002_Willow/Size_Class | Parcel number | Area-ha | Share of total planted area (%) |
|------------------------|---------------|---------|---------------------------------|
| 0,1-0,99 | 195 | 122 | 0.5 |
| 1,00-1,99 | 305 | 447 | 1.85 |
| 2,00-2,99 | 224 | 549 | 2.1 |
| 3,00-5,99 | 489 | 2111 | 8.1 |
| 6,00-9,99 | 348 | 2699 | 10.4 |
| 10,00-15,00 | 258 | 3168 | 12.2 |
| 15,00-20,00 | 154 | 2679 | 10.3 |
| 20,00- | 359 | 14189 | 54.8 |

Table A3 Number of willow parcels and size distribution in 2008 within study area

| 2008_Willow/Size_Class | Parcel number | Area-ha | Share of total area (%) |
|------------------------|---------------|---------|-------------------------|
| 0,1-0,99 | 317 | 196 | 0.7 |
| 1,00-1,99 | 427 | 638 | 2.28 |
| 2,00-2,99 | 316 | 781 | 2.8 |
| 3,00-5,99 | 644 | 2884 | 10.3 |
| 6,00-9,99 | 488 | 3462 | 12.4 |
| 10,00-15,00 | 288 | 3511 | 12.6 |
| 15,00-20,00 | 171 | 2948 | 10.5 |
| 20,00- | 352 | 13423 | 48 |

Table A4 Number of willow parcels and size distribution in 2014 within study area

| 2014_Willow/Size_Class | Parcel number | Area-ha | Share of total area (%) |
|------------------------|---------------|---------|-------------------------|
| 0,1-0,99 | 577 | 330 | 3.7 |
| 1,00-1,99 | 547 | 802 | 9 |
| 2,00-2,99 | 377 | 924 | 10 |
| 3,00-5,99 | 574 | 2468 | 27.4 |
| 6,00-9,99 | 247 | 1854 | 20.6 |
| 10,00-15,00 | 121 | 1446 | 16 |
| 15,00-20,00 | 39 | 660 | 7.3 |

| | | | |
|--------|----|-----|---|
| 20,00- | 20 | 550 | 6 |
|--------|----|-----|---|

Table A5 Number of poplar parcels and size distribution in 2002 within study area

| 2002_Poplar/Size_Class | Parcel number | Area-ha | Share of total area (%) |
|------------------------|---------------|---------|-------------------------|
| 0,1-0,99 | 4 | 2 | 0.3 |
| 1,00-1,99 | 7 | 10 | 1.7 |
| 2,00-2,99 | 4 | 10 | 1.7 |
| 3,00-5,99 | 5 | 20.5 | 3.5 |
| 6,00-9,99 | 6 | 45.5 | 7.8 |
| 10,00-15,00 | 3 | 33 | 5.7 |
| 15,00-20,00 | 2 | 37.4 | 6.5 |
| 20,00- | 11 | 422 | 72 |

Table A6 Number of poplar parcels and size distribution in 2008 within study area

| 2008_Poplar/Size_Class | Parcel number | Area-ha | Share of total area (%) |
|------------------------|---------------|---------|-------------------------|
| 0,1-0,99 | 30 | 15 | 1.6 |
| 1,00-1,99 | 23 | 35.6 | 3.7 |
| 2,00-2,99 | 11 | 27.3 | 3 |
| 3,00-5,99 | 20 | 85 | 9 |
| 6,00-9,99 | 12 | 88.3 | 9 |
| 10,00-15,00 | 9 | 113 | 12 |
| 15,00-20,00 | 6 | 107.5 | 11 |
| 20,00- | 13 | 474 | 50 |

Table A7 Number of poplar parcels and size distribution in 2014 within study area

| 2014_Poplar/Size_Class | Parcel number | Area-ha | Share of total area (%) |
|------------------------|---------------|---------|-------------------------|
| 0,1-0,99 | 371 | 188 | 11.5 |
| 1,00-1,99 | 141 | 203 | 12.5 |
| 2,00-2,99 | 83 | 202 | 12.4 |
| 3,00-5,99 | 74 | 311 | 19 |
| 6,00-9,99 | 30 | 221 | 13.5 |
| 10,00-15,00 | 17 | 205 | 12.5 |
| 15,00-20,00 | 7 | 125 | 7.7 |
| 20,00- | 7 | 169 | 10.4 |

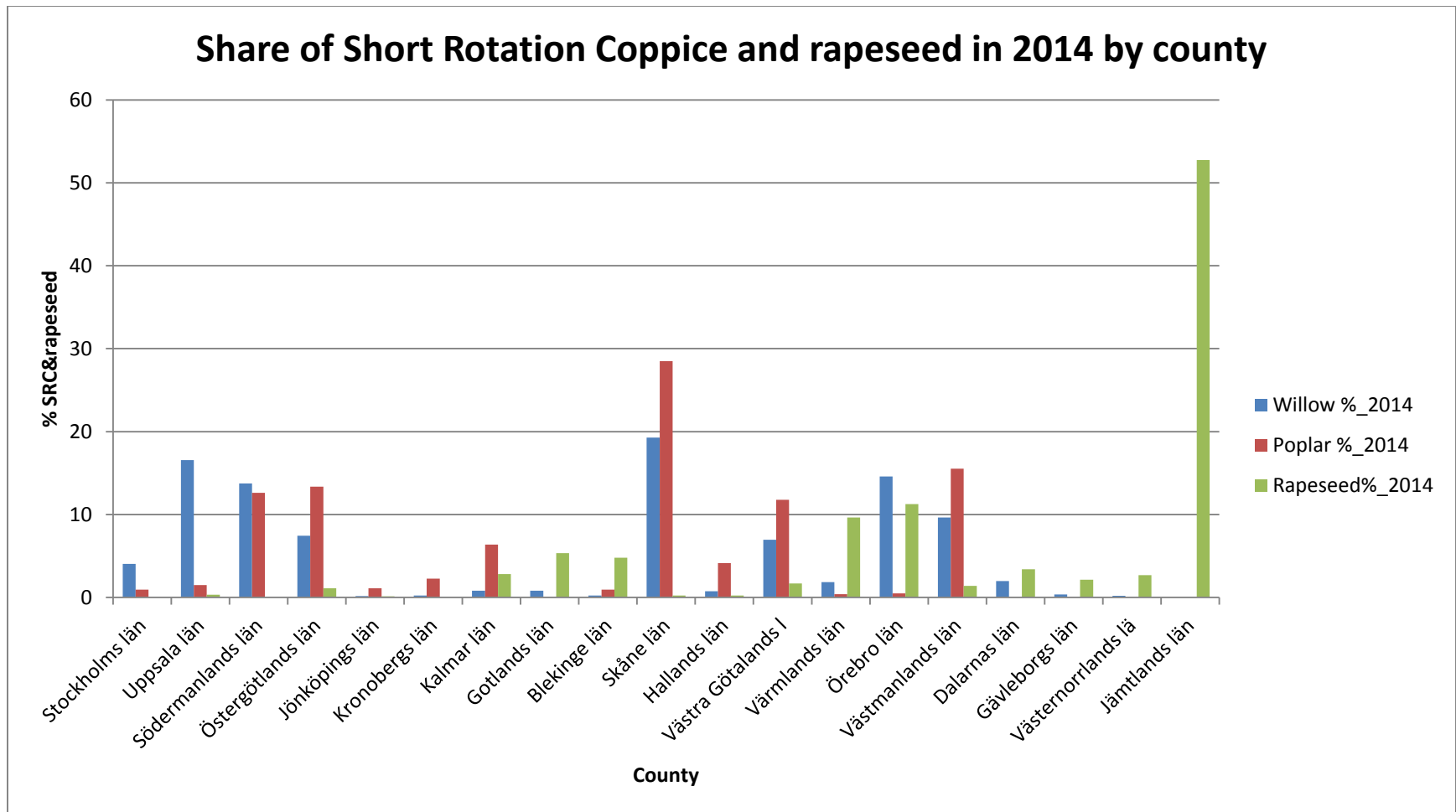


Figure A1 Share of Short Rotation Coppice and rapeseed area of total planted area in each county within study area in 2014

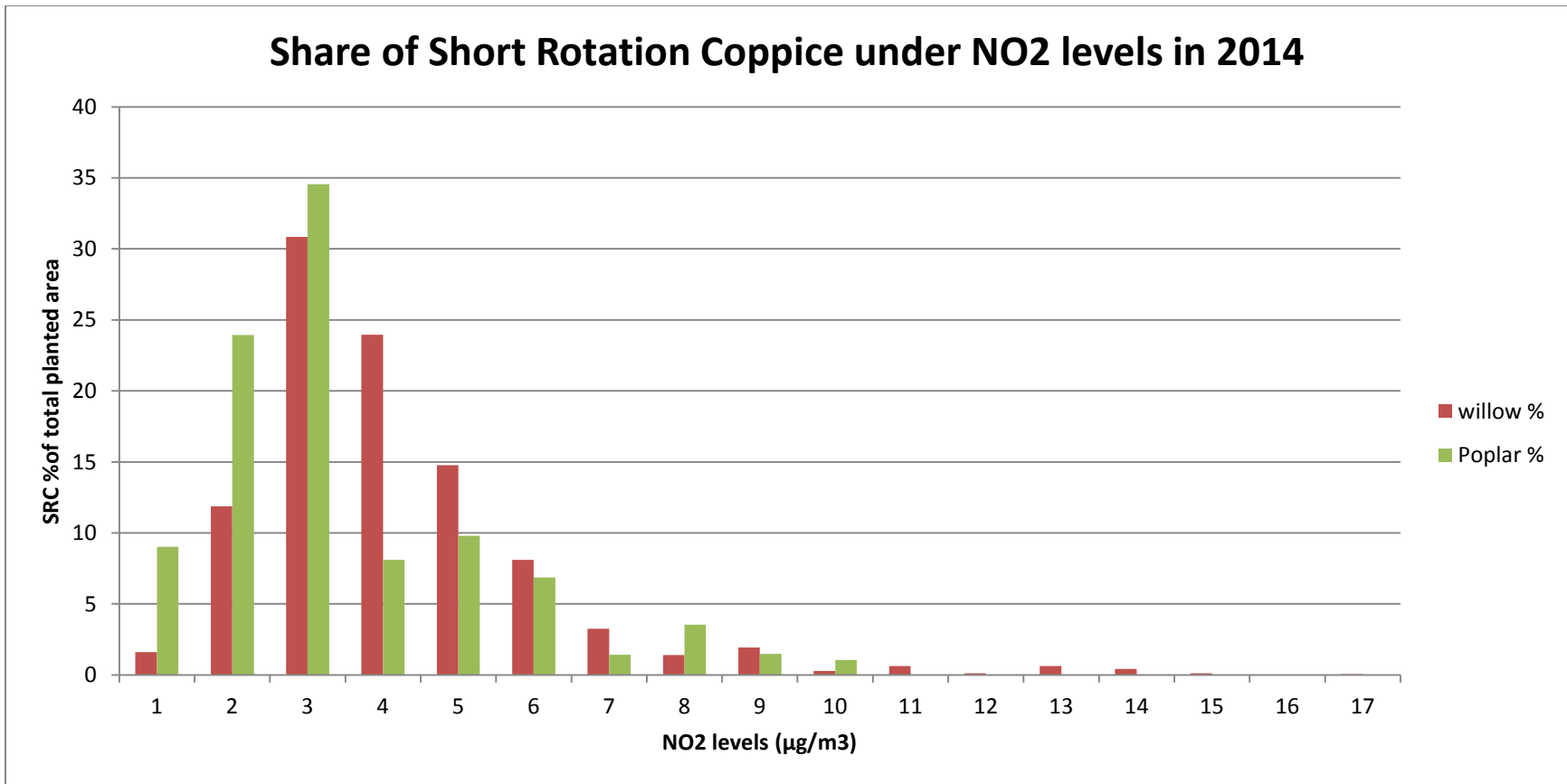


Figure A2 Share of short rotation coppice of total planted area under NO₂ level background in 2014 within study area

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