ASSESSING SHORT ROTATION COPPICE POPLAR BIOMASS AND ITS DETERMINANTS ON FORMER ARABLE LAND IN CZECH REPUBLIC

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In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

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Brno 2017

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Acknowledgements

I would like to express my sincere gratitude to my supervisor prof. Ing. RNDr. Michal Vladmir Marek, DrSc. (Director Global Change Research Institute, CAS) who has enormously supported my Ph.D. study and research. I am very much grateful to prof. Ing. Mgr. Miroslav Trnka, Ph.D. and Ing. Milan Fischer, Ph.D. for providing me their necessary inputs. I am also thankful to prof. Ing. Zdeněk Žalud, Ph.D. (Head of the Institute of Agrosystems and Bioclimatology, Mendel University in Brno) for their support and inspiration. Special thanks to prof. Dr. Rienhart Ceulemans, dr.hon.c.mult. (Director, Research Center of Excellence Plant and Vegetation of Biology, Antwerp, Belgium) for his discussion, inspiration, suggestions and sharing his experience with me during processing of the data and writing my Ph.D. thesis.

I also acknowledge Mgr.Ina Kyslevoa for helping in statistical analysis and Jan Saglena for providing me pictures for my thesis. I also extend my sincere thanks to all the members of the Department of Bioclimatology and Agroforestry system, Ing. Matej Orsag, Ing. Gabriela Pozanikova and Eva Pohankova for helping in the field experiment. It is my pleasure to thank Dr. Ankush Prasad and M.Sc. Ketaki Vasant Phadke for proof reading of my Ph.D. thesis. I extend my gratitude to my friends Aditya, Deepak, Rajbardhan, Ravi, Santosh, Swati, Tomas, Vinay and Zora for delighting and creating a home environment away from home in Czech Republic. It was a pleasure to share the duration of doctoral studies with them. It is also a pleasure to mention my good friends Deepoo, Prafulla, Shakeb, Vimal and Vivek for their friendship and encouragement.

Last but not least, I would like to pay high regards to my parents and brothers. This thesis would not have been possible without the strong faith, support and encouragement from them. I extend my love to my sisters Archana and Mamta. I would also like to thank everyone who have not been mentioned here, but have supported me knowingly and unknowingly.

This research work was supported by the Ministry of Education, Youth and Sports of CR within the National Sustainability Program I (NPU I), grant number LO1415 and Global Change Research Institute (Project: CzechGlobe – Centre for Global Climate Change Impacts Studies, Reg. No. CZ.1.05/1.1.00/02.0073) Brno, Czech Republic. The study was also supported by Czecos (32/4001) and the experiments were partially funded by Internal Grant Agency (IGA, 53/2014), Mendel University in Brno, Czech Republic.

Declaration

I hereby declare that the dissertation entitled "Assessing short rotation coppice poplar biomass and its determinants on former arable land in Czech Republic" to be submitted for the degree of doctor of philosophy as my original work and this dissertation has not been submitted for any award of degree, diploma, or fellowship. I have written this dissertation and where other information's have been used, they have been acknowledged in the "References".

Place: Brno Signature

Date:

List of Publications

Tripathi, A. M., Pohankova, E., Pokorny, R., Fischer, M., Orság, M., Torres, C. P. G., Trnka, M., Marek, M. V., (2016) Long term measurement of leaf area index and radiation use efficiency in short rotation coppice poplar cultures and cereal crops. *Conference 24th European Biomass & Exhibition, at Amsterdam*, http://www.etaflorence.it/proceedings/.

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Summary

To meet the increasing energy demands, caused by the growing world population and industrialization while mitigating anthropogenic CO_2 emissions in the context of global warming, many substitute renewable energy sources are being explored as a consequence of which, research on biomass energy has increased to a greater extent in the recent years. Other best known renewable energy sources are solar, wind and water. Nonetheless bio-energy, either extracted from biomass waste streams or actively cultivated biomass, is one of the most promising and readily available renewable energy sources on the globe in the near future. Definitely, biomass may have the potential to replace fossil and electric fuel as the primary source of heating in Czech Republic and other European Union regions as well. In addition to forest coppice biomass, fast growing short rotation coppice (SRC) trees such as willows (*Salix*) and poplar (*Populus*) have a substantial potential of storing carbon (C), and has been considered as a sustainable source of woody dry mass. Woody dry mass production, energy efficiency and economic profitability of poplar are important and essential to be studied in Czech Republic.

The aim of this Ph.D. thesis was to predict standing woody dry mass, maximize the productivity and quantify the determinants of poplar clone J-105 (*Populus nigra* × *P. maximowiczii)* under SRC management on former arable or agricultural land in Czech Republic. This Ph.D. study was carried out in Domanínek, Czech Republic (49°31´N, 16°14´E) which is part of the Bystřice nad Pernštejnem city in the Czech-Moravian Highlands at an altitude of 530 m above the sea level (a.s.l.). Plantations were established with single stem hardwood cuttings in April 2001 and 2002 with total area of 1.5 and 2.85 ha, respectively in high density (9,216 trees ha^{-1}) for verification purposes and to test the performance of poplar clone J-105 on former arable land. Before plantation, land was being used for cultivating cereals and potatoes.

The plantation was established with no irrigation, fertilization and herbicide treatments. The plantations were harvested above 15-20 cm from base in winter 2008/2009 (established in April 2001) and 2009/2010 (established in April 2002). In this thesis, short rotation woody

coppice (SRWC) plantations are mentioned as SRWC1 (coppice established in 2009) and SRWC2 (coppice established in 2010), respectively. In spring 2009 (at the beginning of second rotation) SRWC1 was divided into four randomized blocks and treated with three different fertilizers such as minerals [Nitrogen (N), Phosphorus (P), and Potassium (K)], sewage sludge and ash, lime and control (without any treatment of fertilizer).

In the plantation SRWC2, no further (at beginning of second rotation-coppice) fertilizer treatment was applied. For the prediction of standing aboveground woody dry mass (AGWDM) in fertilizer treatments and control, allometric equations were developed. The allometric equations thus developed may be considered robust and site specific for poplar clone J-105. After the successful development of allometric equations standing annual AGWDM was estimated followed by annual inventory at the end of each growing season.

There were no significant differences observed in allometric equations for AGWDM among the fertilizer treatments (including control) within the year over four years of study from 2011-2014. This experiment was repeated in plantation SRWC2, for which the allometric equation was developed separately, for the purpose of allocation of the aboveground and belowground woody dry mass (BGWDM) at the same site. In this plantation for estimation of AGWDM, allometric equation was developed in 2011 (after two years of plant growth in coppice) and for BGWDM, the equation was developed in 2014 (after more than four years of plant growth in coppice).

In SRWC2 plantation, dynamics of annual and cumulative above and belowground woody mass were estimated over four years from 2011-2014, where average AGWDM were observed from 8.29 to 11.02 t ha^{-1} $year^{-1}$ and average annual BGWDM varied between 2.50 to 3.02 t ha^{-1} $year^{-1}$.

Growth and wood production mainly depend on photosynthetic area and light efficiency. Therefore, leaf area development including leaf area index (LAI) and leaf area duration (LAD) and radiation use efficiency (RUE) was studied to find a suitable determinant for aboveground woody dry mass production. In the results, maximum leaf area index LAI_{max}

was observed to be 9.5 after four years of plant growth in coppice, maximum number of LAD was 185 days after two years of plant growth in coppice and maximum RUE was observed to be 1.3 gMJ^{-1} in GS4 (growing season four) after four years of plant growth in coppice. LAI and LAD showed a strong positive correlation for AGWDM (R^2 values ~1) while RUE showed a moderate positive correlation with AGWDM, where R^2=0.50 (p=0.52).

This implies that AGWDM is strongly dependent on LAI and LAD. To conclude a robust and site specific allometric equation was developed for poplar clone J-105 and also, this study confirmed that, there was no significant impact of fertilizers for maximizing the AGWDM production on former arable land. For determinants of AGWDM, it confirmed that LAI, LAD and RUE could be a good and reliable predictor of standing AGWDM in SRC poplar clone J-105 on former arable land in Czech Republic.

Keywords: biomass, bioenergy**,** fertilizer, leaf area index, radiation use efficiency, *Populu*s, fast growing tree, short rotation coppice.

Souhrn

Bio-energie, která je buď získávána z odpadu z biomasy, nebozískaná z produkované biomasy, patří k velmi perspektivním zdrojům i pro blízkou budoucnost. Biomasa má jistý potenciál pro alternativní náhradu fosilních paliv ~~a~~ Perspektivní se zdá produkce energetické biomasy v systémech výmladkového lesa, využívajících rychle rostoucí stromy s rychlým cyklem (SRC), jakou jsou (*Salix*) a topoly (*Populus*), která i mají velký potenciál pro skladování uhlíku (C);

Cílem této PhD práce bylo otestovat, zdali konkrétní výmladkový porost má potenciál pro vysokou produkci biomasy a zdali můžeme pro tento účel efektivně využít klony topolu J-105 (*Populus nigra* × *P. maximowiczii)* v systému SRC rostoucího na původní. Výzkum byl realizován na lokalitě Domanínek (49°31´N, 16°14´E, 530m n.m). Sledovaný výmladkový porost byl záložen v letech 2001 a 2002. Porost byl založen na původní orné půdě. Sklizen biomasy byla realizována v letech 2008/2009 (z prostorů zakládaných v dubnu 2001) a v letech 2009/2010 (z porostu zakládaných v dubnu 2002).

V této práci jsou použity výmladkové porosty označené souhrnně jako SRWC, a to prostory založené v roce 2009 jsou označovány pod SRWC1 a prostory vysazované v roku 2010 jsou označené jako SRWC2. Na jaře roku 2009 (při zahájení druhého cyklu) SRWC1 byla rozdělena na čtyři náhodné části nebo bloky, které byly ošetřovány třemi různými způsoby; a minerální látky [dusík (N), fosfor (P), a draslík (K)], kaly z odpadních vod a popílky, vápno a plocha kontrolní. Porost SRWC2 byl ponechán bez zásahu. Pro predikci stávající dřevinné sušiny (AGWDM) byly stanoveny konkrétní alometrické rovnice, které jsou specifické pro daný klon topolu. Pomocí alometrických rovnic byl odhad každoroční AGWDM, které pak byl následně využit i ke každoroční inventarizaci.

Nebyly pozorovány žádné významné rozdíly u výpočtů v alometrických rovnicích pro AGWDM (včetně kontroly) v průběhu roku to po celé období čtyř let v rámci studie v letech 2011-2014. Tento experiment byl opakován i v ve výsadbě SRWC2, pro který alometrická rovnice byla vyvinuta odděleně. U výsadby SRWC2 - dynamika každoročního kumulativního nadzemního i podzemního růstu dřevinné sušiny byla odhadována na dobu čtyř let 2011-2014, kde bylo průměrné AGWDM pozorováno od 8,29 na 11,02 t ha^{-1} na rok ^{1} a průměrné každoroční BGWDM se lišilo mezi 2,50 na 3,02 t ha^{-1} na rok^{-1}. Růst a produkce dřeva závisí hlavně na výkonosti fotosyntézy a na efektivitě transformace světelné energie Slunce do tvořící se biomasy.

Proto byl sledován rozvoj velikosti listu včetně indexu velikosti listu (LAI) a trvání velikosti listu (LAD) a efektivita využití záření (RUE). Byla stanovena maximální hodnota indexu listové plochy-LAI_{max}, který dosahuje po čtyřech letech růstu hodnoty 9,5. Maximální počet dnu existence listové plochy -LAD byl 185 dnů .

Maximální RUE bylo bylo 1,3 g MJ^{-1} u po čtyřech letech růstu. LAI a LAD vykazují velmi silnou pozitivní korelaci pro AGWDM (R^2 hodnotí ~1); zatímco RUE ukázalo mírnou pozitivní korelaci s AGWDM, kde R^2=0.50 (p=0.52). Místně specifická alometrická rovnice, která vyvinuta pro klon topolu J-105 ukazuje na skutečnost že není žádný významný vliv hnojiv pro maximalizaci AGWDM na původních obdělávaných půdách. Pro determinant AGWDM, bylo potvrzeno, že LAI, LAD a RUE by mohly být dobrými a spolehlivými predikátory stávajícího AGWDM u SRC klonu topolu J-105 na původních obdělávaných půdách.

Klíčová slova: biomasa, bioenergie**,** hnojivo, index plochy listu, efektivita využití záření, *Populu*s, rychle rostoucí stromy, výmladkový porost topolu

Abbreviations

AGWDM=Aboveground woody dry mass

ANOVA= Analysis of variance

APAR= Accumulated photosynthetic active radiation

BGWDM= Belowground woody dry mass

C= carbon

CI= Confidence interval

CO2= Carbon dioxide

Cr= Coarse root

DBH= Diameter breast height

DM= Dry mass

DOY= Days of year

FAO= Food agricultural organization

GHG= Greenhouse gas

GS= Growing season

IEA= International Energy Agency

IEO= International Energy Outlook

K=Potassium

LAD= Leaf area duration

LAI=Leaf area index

LAI_{avg}= Average leaf area index

LAI_{max}= Maximum leaf area index

N=Nitrogen

P= Phosphorous

PAI= Plant area index

PAR= Photosynthetic active radiation

RUE= Radiation use efficiency

SD= Standard deviation

SE= Standard error

SRC= Short rotation coppice

SRF= Short rotation forestry

SRWC= Short rotation woody coppice

SRWCs= Short rotation woody crops

WAI= Wood area index

Chapter 1

1. Introduction

1.1. Biomass for energy

In the current scenario, global growth of society and industrialization has increased world's energy consumption. The demands on energy usage seem to be ever increasing. The industrial revolution began with the use of fossil fuels such as coal, oil and natural gas. The International Energy Outlook (IEO) recently reported an increase of the global energy consumption by more than 50% from 2010-2040 (IEO 2013). Currently, the global energy supply is about 81% fossil fuel-based in 2012, (International Energy Agency- IEA 2014). A higher consumption of primary energy is more than supply of oil and natural gas in many industrialized countries thus increasing their energy dependency, with 54% of the European Union (EU) gross inland energy use being imported in 2010 (Eurostat 2013). The release of enormous amount of greenhouse gases (GHGs) into the atmosphere through burning of fossil fuel has been altering the global climate and endangering our environment. Fossil fuels are consumed in high amount because of fast industrialization and have become a reason for exhaustion in last few years. As a consequence there is an exploration of other energy sources and resulted reduction in the GHGs emissions from fossil fuels (Smil 1994).

To fulfill the energy demands of our growing society there is a need for alternative energy sources, as the fossil energy use is responsible for about 85% of the anthropogenic carbon dioxide (CO_2) emissions produced annually and it's the lifetime of proven reserves being estimated at only 112 years (IEA, 2011), (Integovernmental Panel on Climate Change- IPCC 2012). The CO_2 emission increases due to anthropogenic activity by human interference such as urbanization, deforestation and use of fossil fuels. Because of long term deposition duration in the atmosphere and emission rate, CO_2 is the main important greenhouse gas (GHG). IPCC (2007) have reported that increasing the atmospheric GHG concentrations is related with a changing climate as evidenced from rising global average sea level and temperature.

By 2100 global temperature may be ranging between 1.8 and 4.0^{o}C depending on the globalization rate (IPCC 2007). Distinct fossil energy, renewable energy is any form of energy from sun, biotic or geophysical sources being replenished by natural processes at an equal or higher rate than their rate of use (IPCC 2014). Despite of hydropower, solar, wind and geothermal energy, bioenergy (derived from biomass) has a largest share (80%) of the global renewable energy supply in 2008 (IPCC 2011). Bioenergy is a dynamic energy source that may replace fossil fuels in all its forms, in comparison to other renewables. IPCC (2012) have reported that globally, renewable energy accounted for 12.9% of total 492 EJ of primary energy supply (**Figure 1**), of which the biggest contributor was biomass (10.2%) though with the majority being traditional biomass used in household application in developing countries in 2008.

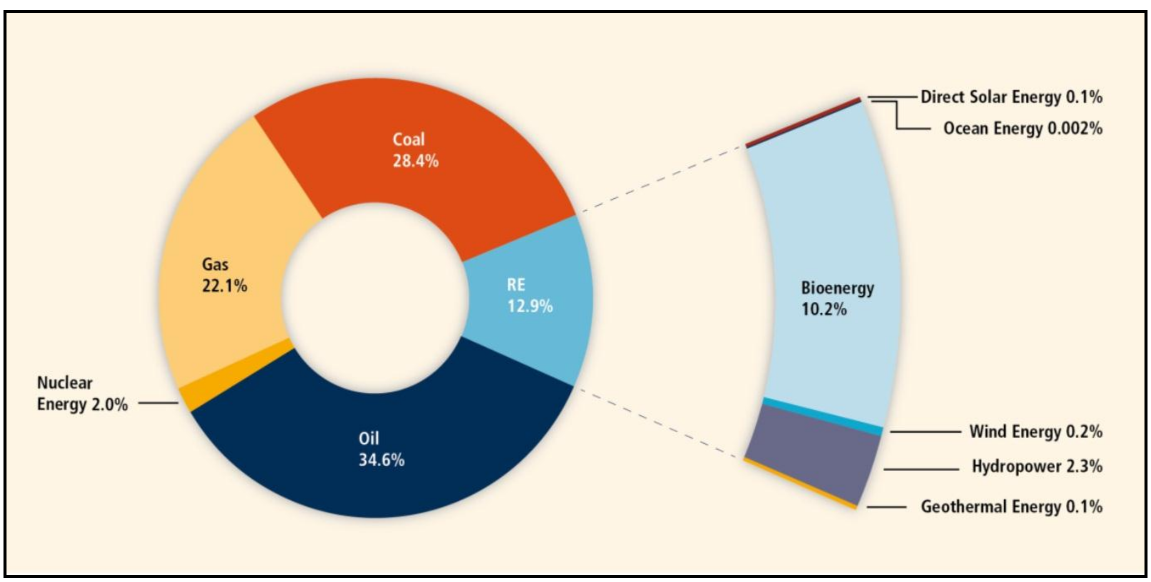

Figure 1: Shares of energy sources in the global primary energy supply of 492 EJ in 2008 (adapted from Broeckx 2013; source IPCC 2012).

Bioenergy forms 10% of primary energy worldwide, and it is one of the main renewable energy resources for the future due to its great utility, flexibility, availability, and favorable environmental, social and economic characteristics (IEA, 2014). Bioenergy can be extracted from residues of agricultural, forestry and all forest products, herbaceous, aquatic plants, municipal, animal and human wastes. Around 33% bioenergy (generated from biomass) is generated in developing countries, however, in developed countries biomass energy is generated about 3% only. Contribution of biomass to energy in Europe was estimated to be 10-12 % by 2010 (Energy Information Agency-IEA 2011). European Union (EU) aims to reduce the use of energy consumption and increase the energy generation from Renewable Energy Sources (RES), together with energy savings and increased energy efficiency (European Parliament 2009).

The European Council (EC) has set an obligatory target of a 20% share of energy from RES in overall community energy consumption by 2020 and obligatory 10% at least minimum target to be achieved by all member of EU states for the share of biofuel consumption, sustainability and second generation biofuel to be cost effective and commercial available directive 2009/28/EC. New target is set to consume at least a 27% share of renewable energy by 2030. Pursuant to this directive obligatory target for Czech Republic is 13% share of energy from RES in total final energy consumption by 2020.

In 2010, primary renewable energy (70%) was generated by biomass and waste. This number may drop by 62% in 2020 and to 56% in 2030. There are chances that these numbers may fall even more by 50% by 2050. World total primary energy supply from 1971 to 2012 by numerous sources of fuel mentioned in **Figure 2** (IEA report 2014).

Biomass is currently the most promising RES for all the members of EU states including Czech Republic, as it has contributed tremendously (about 90.9% share in total EU RES in 2010) to final energy consumption for heating and cooling (European Parliament 2009). In Czech Republic, the biomass market is still under developing phase while major progress has been done in biofuel sectors (Bioazul 2010). About 63% of biomass energy is consumed from the total RES in Czech Republic and therefore it is considered to be an important energy consumption strategy playing an important role in the Czech Republic's energy consumption strategies because 63% of biomass energy is consumed in total of RES.

In 2010 biomass covered about 97% of RES in the final energy consumption for heating and cooling, and the National Renewable Energy Action Plan (NREAP) expects Czech Republic to maintain this high percentage by 2020.

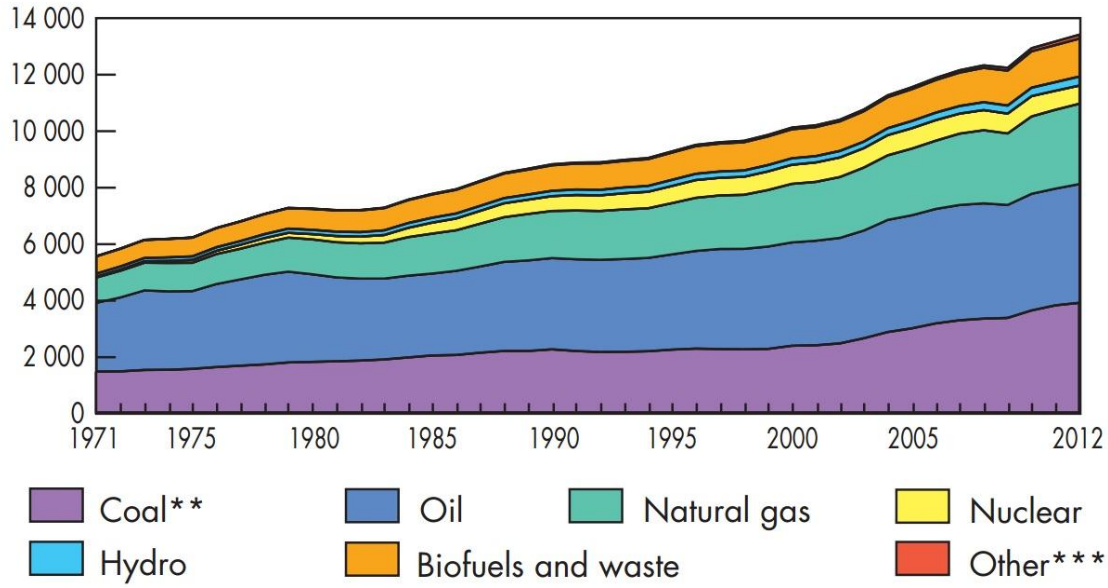

Figure 2: World* total primary energy supply from 1971 to 2012 by fuel (Mtoe), IEA report (2014).

*World includes international aviation and international marine bunkers, **in these graphs, peat and oil shale are aggregated with coal, ***includes geothermal, solar, wind, heat, etc.

Such a need for rapid increasing growth of renewable energy generation in the expected use and biomass production to meet the EU targets (EU Comission 2014) cannot be secured without the use of large areas of agricultural land for the cultivation of biomass for energy purposes. The development of growing biomass for energy purposes on agricultural land is still in its initial phase and use of biomass for energy in the EU and the Czech Republic are still below its potential (Breu et al. 2008). The development of the use of biomass for energy purposes is hereby to be understood in direct relation to the, energy security, food security and mitigation of the climate change. In this context, fast-growing woody energy crops deserve to maintain the required level of food security, energetic security and sequestration of CO_2. Nevertheless these facts, the areas of bioenergy plantations in the Czech Republic are still low compared with the other neighboring countries in Europe (Fischer et al. 2010).

In spite of, multiuse of bioenergy crops, for successful establishment and selection of suitable sites, it is very important to understand growth and production requirements of particular tree species for the bioenergy purposes.

1.2. Short rotation coppice (SRC)

1.2.1. Explanation

The concept of short rotation coppice (SRC) for bioenergy production comes from 1960's (Hansen 1991), some fast growing trees can be cut down to low stem (or stool) in order to stimulate re-growth from the stump and/or from the roots to increase biomass production in a coppice management mainly grown on arable land (Laureysens et al. 2005; Nordh & Verwijst 2004). The SRC is defined as a cultivation of fast-growing woody crops where the aboveground biomass is periodically harvested after 2-8 years of plant growth. Usually, the rotation cycle varies from 2 to 6 years (with an expected life span of 15-30 years) (Ceulemans et al. 1996; Walle 2007; M. S. Verlinden et al. 2015; Fischer et al. 2013). After the oil crisis in 1970's, and after EU made a policy (1980s) in response to the agricultural overproduction, over fertilized agricultural land, renewed the interest in SRC (Dillen et al. 2010, 2011).

The SRC of fast growing woody biomass production is one the best source of alternative energy (Ceulemans et al. 1990; Laureysens et al. 2005; Kauter et al. 2003; M.S. Verlinden et al. 2015). Presently, mitigation of the climate change and energy security together with spectacular progress in tree genomics and biotechnology has generated renewed interest in SRC (IEA 2011 & 2014). To achieve maximal potential yields, SRCs are preferably established on arable land or loam- or clay-containing soils with adequate water and nutrient availability (Marron et al. 2007; Ceulemans & Deraedt 1999; Trnka, Trnka, et al. 2008). Before planting, site preparation includes ploughing to assure good rooting and harrowing to even out the field. The field should be completely weed-free prior to planting, either through chemical or mechanical weeding which reduces competition of water, nutrient and light, as

SRC do not endure shade (Guidi et al. 2013; Otto et al. 2010). In SRC cultures for bio-energy, fast-growing trees – most commonly poplars (*Populus spp.)* and willows (*Salix spp.)* are utilized. Due to the ability of most *Populu*s and *Salix* species to reproduce easily by vegetative propagation, SRC plantations are usually established from unrooted hardwood cuttings (Keoleian & Volk 2005; Heller et al. 2003; González-García et al. 2012; González-García et al. 2013, **Figure 3**). These cuttings are harvested from one-year old or older stems during the dormant season and their size generally ranges from 20 to 30 cm and planting densities are very high which varies from 6,000 to 20,000 cuttings ha^{-1} (Sage 1999; L S Broeckx et al. 2012; Walle 2007; Verlinden et al. 2015). It can be planted in two designs, namely single-row and double-row designs; planting schemes have been described and applied, each with their advantages and disadvantages (Schweier & Becker 2012b; Spinelli 2008; Spinelli & Visser 2009; Bonhomme et al. 2008). The single-row design, often used in Italy, facilitates weed management; but lower planting densities induce longer rotation cycles while double-row design introduced in Sweden (known as Swedish design) for willows usually have a cutting density of 6000-7000 ha^{-1} (Spinelli et al. 2009). In this design, trees are planted in rows with alternating distances of 0.75 m and 1.50 m, the wheels of agricultural machines straddling the narrow row. In this scheme there is fast canopy closure; hence maximal light capture is reached shortly after planting. During the establishment year, initial planting density determines the mortality rate i.e. very low and the length of the rotation cycle and vice versa; the higher the planting density, the shorter the rotation cycle (Heilman 1999; Ruttens et al. 2011; Strauss et al. 2001; Ceulemans & Deraedt 1999; Wilkinson 1999), but it may be dependent on genotype as well (Laureysens et al. 2005; Nassi O Di Nasso et al. 2010; Paris et al. 2011; Broeckx et al. 2012a). SRC poplar has fast growth and high yield production than the uncoppiced (single-stem stand) management system of poplar and willows (Herve & Ceulemans 1996; Johansson & Hjelm 2012; Wullschleger et al. 2002; Walle 2007).The trees are often coppiced at the end of the first rotation cycle (2-5 years) that could be easily converted into coppice (multi-stem stand) system to enhance the growth performance for the next rotation.

The first coppice often re-grows after one or two growing seasons from the established root system (Afas et al. 2005; Dillen et al. 2013; Nassi O Di Nasso et al. 2010). In poplar, there is stronger apical dominance as compared to willow, so it can grow faster than the willow after the coppice (Ceulemans et al. 1996).

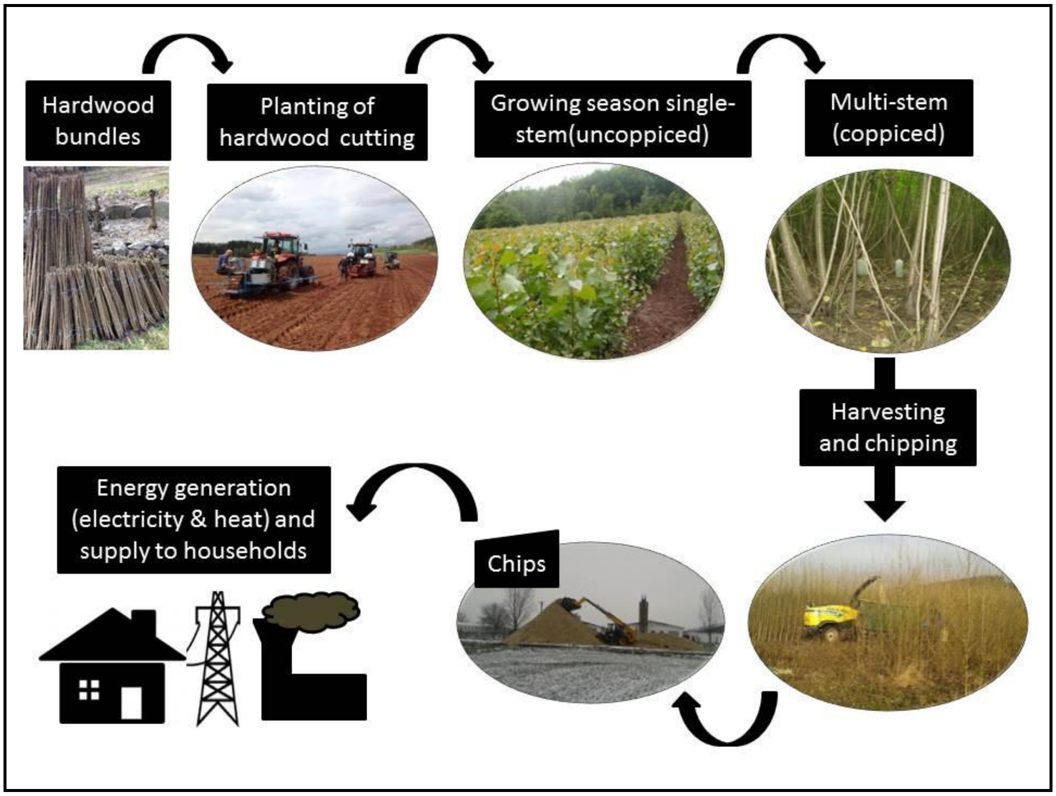

Figure 3: The concept of poplar short rotation woody coppice (SRWC) cultivation for bioenergy production (modified from Broeckx 2013; Antwerp 2013).

Generally coppicing is thought to regenerate growth, at least in the early rotations of SRC, and obviously avoids replanting expenses and this coppice systems are easily cut with agricultural harvester (Laureysens et al. 2005; Ceulemans et al. 1996; Tubby & Armstrong 2002). Preferably winter time is good for harvesting of SRC because during the winter soils are frozen; preventing soil compaction due to the heavy tractors and harvesters thus decomposing the litterfall to maintain the nutrient cycle in coppice (Björkman et al. 2004; Schweier & Beckar 2012; Mitchell et al. 1999; Santangelo et al. 2015). Two different harvesting strategies can be applied; either simultaneously coppicing and chipping in situ, or the crop is cut with the whole stem and chipped off at later operations (Vanbeveren et al. 2015; G. Berhongaray et al. 2013). The harvested biomass in form of chips can be left for drying, dried wood chips can then be used as renewable energy resource to generate electricity through co-combustion/gasification or for liquid transport fuels through chemical fermentation/thermo-chemical conversion with the calorific values around 19 GJ ton^{-1} dry mass (Verlinden et al. 2013). The electricity generation alters between 1450-1950 $kWhton^{-1}$ depending on the conversion efficiency (27.7% and 37.2% for combustion and gasification, respectively, (Djomo et al. 2011). The yields of woody dry mass (DM), ranges between 5 to 16 Mg $ha^{-1}year^{-1}$ for various site conditions such as nutrients, climatic conditions and soil water availability (Ceulemans & Deraedt 1999; Djomo et al. 2011). In the Czech Republic electricity consumption is 6288.533 kWh per capita in year 2011 (data from World Bank), while taking an average yield of 11 t ha^{-1} $year^{-1}$, the annual electricity consumption could be covered by 1 ha of poplar SRC for a minimum of two households.

1.2.2. Usabilities and restraints

The potential large-scale deployment of SRC plantations for bioenergy requires changes in the environmental impacts such as biodiversity, soil erosion, water use, and greenhouse gas (GHG) mitigation. The environmental effects can be positive or negative, highly dependent on former land use. The richness of biodiversity (ground cover encourages the presence of invertebrates which increase in the number of small mammals and birds, higher species richness of plants, and a comparable diversity and density of soil micro-arthropods) lies in willow SRC plantations as compared to arable control land (Rowe et al. 2009; Volk et al. 2004). It has been a positive impact on soil properties, soil erosion rate, soil texture, soil organic carbon sequestration, and fertility due to reduction of ploughing and water holding capacity, reported for SRC established on previous crop land, nevertheless, if arable land and permanent grassland are replaced, these benefits are obviously less (Rowe et al. 2009; Djomo et al. 2013).

Poplar and willow SRC are characterized by higher water use as a consequence of high transpiration rates, large leaf area and extensive rooting depth as compared to agricultural crops. Productivity may be limited by water availability which reduces the potential of SRC without irrigation in arid and semi-arid zones (Stettler et al. 1996; Lott et al. 2009; Linderson et al. 2007; McKay 2011; Fischer et al. 2013). Additionally, the “phytoremediation” potential of poplar and willow SRC have the ability to take up harmful waste products and lock them away in their woody stems, when established on contaminated sites (Marron et al. 2007; Laureysens et al. 2003; Pajevi et al. 2009; Robinson et al. 2000; Pulford & Watson 2003). Municipal and corporate institutions are more and more encouraged by new research showing the benefits of planting short rotation woody crops (SRWCs) to naturally clean up toxic waste for bioenergy purposes (Djomo et al. 2013; Rockwood et al. 2008). Nevertheless, there is a negative impact of SRWCs on fragmentation, as the SRWCs acts as ecological corridors through which species can migrate between natural areas (Sage 1998). The energetic and ecological viability of SRWCs with poplar and willow have shown very few studies on both the GHG and energy balances e.g. significantly lower GHG emissions and higher energy yields of SRC were found in comparison of coal (Djomo et al. 2011). The financial feasibility is a major constraint in the development of SRWCs for bio-energy production, which is recently concluded that in a review the SRC cultures are not economically viable in most regions without government support (El Kasmioui & Ceulemans 2012). While the successful and profitable story of SRWCs of willow for about 90% electricity consumption in Scandinavian countries motivates to increase the planting of SRWCs (Wright 2002). However, the EU and individual states need to achieve the 20% energy requirement of biomass by 2020 and on other hand due to scarcity of land we need to increase the biomass from SRC (IEA 2011).

1.2.3. Determinants of SRC biomass

The role of fertlizer on agriculture lands have been used with considerable success, from a production and an economic point of veiw (De Wit et al. 2011). In Czech Republic, the majority of fertlizers are applied to annual dryland agricultural crops and, to minor area perennial forages and pasture land (Kopecký & Vojta 2009). Modern improvement in soil testing and soil test interperation have helped farmers manage their fertlizer inputs with greater efficiency (Don et al. 2012).

Practical knowledge into the evolution and enhancement in the productivity of crop from fertilizer application equipment has enabled farmers to place fertilizer where it will be most effective. However, technology has helped increase the efficiency of modern grain farming, on farm profitability is declining and causing climate change as well. To increase the profitability and mitigate the climate change, growing SRC hybrid poplar trees as a crop can be an economical and sustainable option for the farmers (Peterson & Peterson 1992; Joss et al. 2008; Yemshanov & McKenney 2008; Thevathasan & Gordon 1997; El Kasmioui & Ceulemans 2012). On the other hand, under field conditions, crops productivity and growth are demarcated by interception of photosynthetic active radiation (PAR) and by interaction of numerous environmental and physiological factors (Monteith & Moss 1977; Biscoe & Gallagher 1977; Pangle et al. 2009; Ceulemans et al. 1996).

An intercepted light depends mainly on plant leaf area index (LAI), canopy architecture and physiology of plants and the plant growth and productivity under field conditions are primarily dependent on the potential of canopy to intercepted incoming radiation and convert it into yields (Chen & Cihlar 1995; Hikosaka 2005; Nair et al. 2012). The amount of biomass produced per unit of intercepted light is called radiation use efficiency (RUE) and to a large extent it determines the growth and yield in woody and non-woody crops (Sinclair & Horie 1989; Medlyn 1998). Monteith and Moss (1977) defined the concept of RUE, as the ratio between the quantity of accumulated photosynthetic active radiation (APAR: 400-700 nm) and the quantity of dry mass (DM) produced is relatively a conservative parameter. In numerous biomass studies, a linear relationship between APAR, RUE, LAI, leaf area duration (LAD) and crop growth has been found in both woody SRC and agricultural crops as well (Stockle & Kiniry 1990; Stöckle & Kemanian 2009; Borek 2009). The actual RUE is affected by several factors such as temperature (Bartelink 1997), water and nutrient availability (Ahmad et al. 2012; Stöckle & Kemanian 2009). It may also depend on management type such as SRC and genotypes (Dillen et al. 2013; Liberloo et al. 2007; Verlinden et al. 2015; Trnka et al. 2016).

1.2.4. The genus Populus

Poplars belong to the genus *Populus* (family Salicaceae) primarily occurring in North America, well suited for certain conditions and widely spread across the world broad range of ecological habitats. Poplars are dioecious species, with separate male and female trees. The genus is morphologically and ecologically distinguished from each other and divided into six sections (Isebrands & Richardson 2014). Hybrids are largely cultivated from three main sections namely Aigeiros, including black poplar (*Populus nigra* L.) and eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.); Tacamahaca the balsam poplars; and *Populus*, including white poplar (*Populus alba* L.) and the aspens (Isebrands & Richardson 2014). About 90% of the global poplar cultivation belongs to the section Aigeiros (Floate 2004). Most of the hybrids are derived from *Populus deltoides*, primarily crossed with species from the Aigeiros and Tacamahaca sections, because of the ease of hybridization (Heilman 1999). Naturally, poplars are fast-growing pioneer tree species, which are grown under intensive management in short rotation forestry (SRF) and harvested in 2-10 years rotation cycles (Heilman 1999; Dillen et al., 2011a; Isebrands & Richardson 2014). On the other hand the disadvantage of poplars for cultivation is related to their high water demands with high growth and susceptibility to diseases, even though water-use efficiency is highly variable among genotypes and species. Therefore, the large scale genetic diversity has been exploited in selection programs and breeding for high-yielding and disease-tolerant genotypes. Hence, selection and breeding programs have so far mainly focused on straight, single-stem growth, not including coppice ability as a selection criterion. The advantage of hybridization is the combination of specific growth characteristics and heterosis, defined as the superiority of the offspring as compared to the parental average characteristics (Howe et al. 2000). *Populus* is also the first genus for which the genome has been fully sequenced (Isebrands & Richardson 2014). Consequently the latest techniques in molecular genetic mapping, genomics and the physical sequence of poplar are being used to define genes that determine high yield and disease resistance, with the aim of improving this genus for growth across Europe and USA (America) as a bio-energy and timber crop. Globally poplar occurrence was recorded in 2008, about 80 million ha of natural and 5.3 million ha of manmade plantations, (Turral et al. 2011). Poplars are mainly used for wood products such as timber, firewood, furniture, paper and pulp, and as a renewable source of biomass for energy, (Isebrands & Richardson 2014). The cultivation of poplar for bioenergy purposes remains less (Dillen et al. 2011). Besides wood production, poplars is mainly used as wind breaks in Europe and also worldwide in agricultural areas, soil protection, phytoremediation, and reforestation, etc. (Johansson & Karačić 2011; Aylott et al. 2008).

Chapter 2

2. Objective of the thesis

Increasing demand of bioenergy and mitigation of climate change by SRC plantations are sparse, research is needed to estimate the total biomass production on over fertilized or former arable lands. There is a need for future research focusing on growing short rotation trees and SRC cultures such as hybrid poplar and willow under the over fertilized land or use of mineral fertilizers (N, P and K), sewage sludge and ash, waste water, and lime mixture on the former arable land in the Czech Republic, Europe and as well as for other countries. It is unclear whether external nutrient supply or fertilizer application determines the growth and production of total biomass for the SRC cultures of hybrid poplar on former arable land. When searching for the growth and accumulation of biomass in hybrid poplar clone. The overall objective (**Figure 4**) of the thesis is to provide practical information for growers and to improve the knowledge of the determinants of productivity of high-density hybrid poplar under SRC management plantations. Information is needed to develop management's recommendations, cost effectiveness, and identify the role of nutrients and other parameters to contributing productivity in hybrid poplar clone under high-density SRC management in Czech Republic.

To reach the overall objective, the present Ph.D. thesis was planned and the following measurements were considered:

- To develop an allometric equation for the estimation of standing woody dry mass (DM) of selected hybrid poplar clone J-105 in different fertilized and non-fertilized treatments.
- To evaluate the significant or non-significant difference of standing woody DM of selected hybrid poplar clone in fertilized and non-fertilized on over fertilized or former arable (previously used for agriculture) land.

- To assess the annual aboveground productivity and survival rates of selected hybrid poplar clone in SRC management.
- To study the seasonal variation of leaf area development in coppice culture assessed as leaf area duration (LAD) through bud phenology of selected hybrid poplar clone.
- To study the seasonal variation of maximum leaf area index (LAI_{max}) in coppice of selected hybrid poplar clone.
- To study the seasonal variation of radiation use efficiency (RUE) in coppice of selected hybrid poplar clone.
- To estimate the total belowground woody DM of selected hybrid poplar clone under long term SRC management.
- To identify and interpret the relationships of LAI (LAI_{max} & LAI_{avg}), LAD and RUE with growth and woody DM production in coppice of selected hybrid poplar clone.

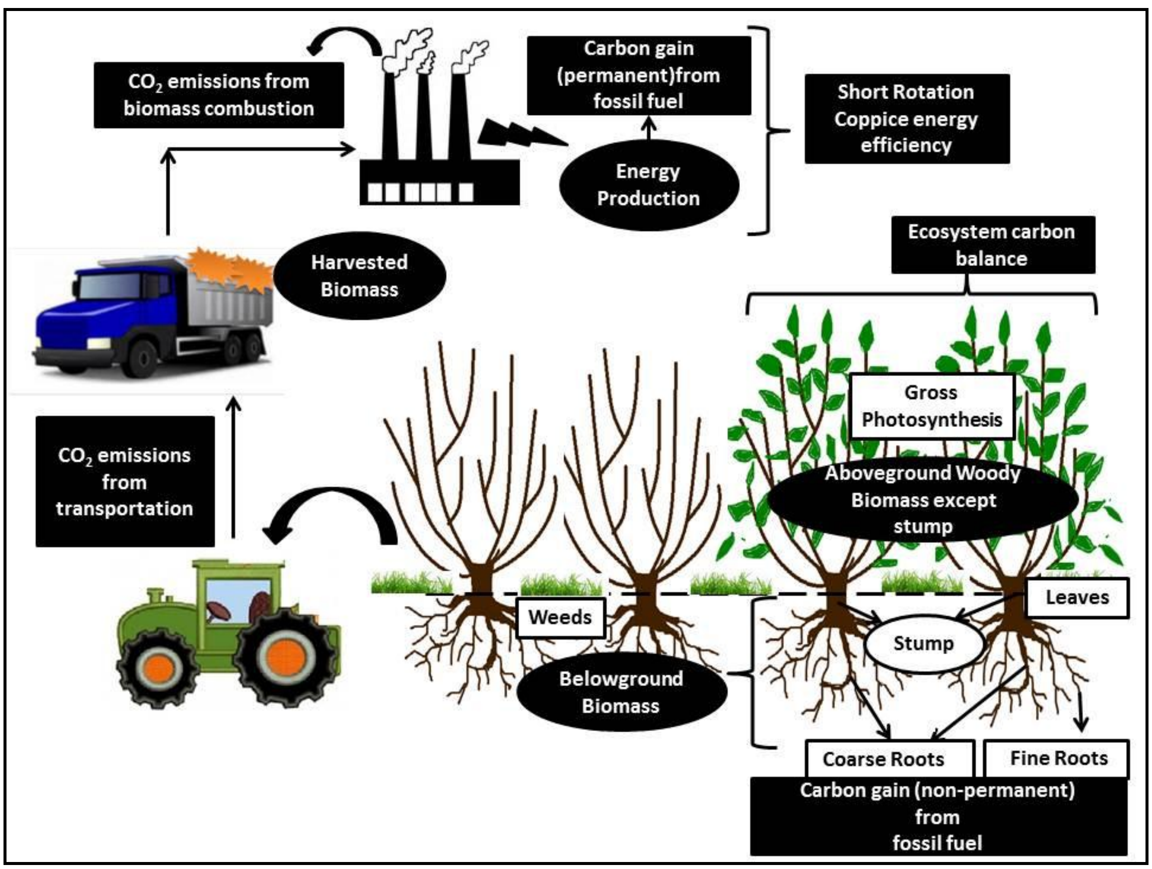

Figure 4: Sketch of the main objectives addressed in the large-scale short rotation coppice (SRC) project, life cycle assessment (LCA), CO_2 sequestration and nutrients basically focus on nitrogen (N).

<u>Chapter 3</u>

3. Review of literature

3.1. Allometric equation for estimation of biomass

For the estimation of total standing biomass and its allocation an allometric equation is required to be derived that will be used to relate the mass of a tree to its physical parameters (Hanson et al. 2002; Yarie & Mead 1988). Biomass estimates are essential to be known prior to harvesting, as it will help to balance the CO_2 in the environment and enable wood production. In traditional forestry, biomass estimates were investigated for several above and belowground tree parts, but most researchers were focusing on the aboveground parts; in particular, stem, branch, crown, stump, and foliage (Don et al. 2012; Clifton-brown et al. 2007; Berhongaray et al. 2013; Broeckx et al. 2014). Allometric equations can be used to estimate aboveground and belowground biomass that are quite difficult to measure in forests, woodlands and savannahs (Basuki et al. 2009). The use of these equations depends on the uniformity of an allometric correlation between tree dimensions and its biomass (Peichl & Arain 2007). The method has applications in many areas, including resource inventories, evaluating the spatial accumulation of carbon (Nickless et al. 2011) and comparisons in biomass distributions between different tree species or between the same species under diverse circumstances (Chaturvedi & Raghubanshi 2015; Archibald 2011; Peichl & Arain 2007).

Many researchers have developed site-specific allometric equations for specific tree species to estimate biomass of trees. These equations differ with varying tree species, areas and separating out size ranges of the tree dimensions, for instance diameter breast height (DBH) (Jenkins et al. 2003). In forest ecosystem destructive sampling of the entire aboveground mass of trees is expensive, difficult and labor-intensive process, and it results in the removal of the trees (Chmura et al. 2007; Q M Ketterings et al. 2001; Quirine M Ketterings et al. 2001; Gehring et al. 2004; Alamgir & Al-Amin 2008; Vann et al. 1998; Jenkins et al. 2003 ;

Nickless et al. 2011). Since the traditional relationships between the uses of stem diameter and the mass of biomass components, such as wood and leaves is rigorous and not easy to determine accurately. Specific allometric equations are derived for particular tree species or for developing multi-tree species models (Wang Zhengquan et al. 1995; Cairns et al. 1997; Niiyama et al. 2010; Chen 2015; Chaturvedi & Raghubanshi 2015). Allometric equations are derived by correlating DBH to the dry weight of the same sampled tree or stem which are extensively studied for larger trees (DBH>2.5) (Yarie & Mead 1988; Arevalo et al. 2007; Volk et al. 2006; Jenkins et al. 2004). In the studies, Felix et al. (2008) and Das et al. (2011), observed that the biomass to stem DBH relationship can be exponential during the first six years of poplar's tree age, however linear growth is also common.

The prediction of biomass and validation of calculations of allometric equations is ensured by the finest curve fitting to the data, therefore, the power equation $W=ae^{bD}$ (where W is the dry weight of the measured tree, a and b are constants, and D is diameter), was used to develop allometric equations based on the two predictors under the assumption of exponential growth (Volk et al. 2004). For linear models see equation 2, - where Ballard et al. (2000) have reported a robust allometric equation (R^2 ~1.0), which is a cost effective measurement technique for estimating standing biomass. Therefore, allometric equations can be a valuable tool for assessing growth rates of a woody crop being vigorously managed, and determining harvest rotations (Tahvanainen 1996). In a literature Telenius (1999), the use of tree height as an additional variable was trialed by some researchers such as Flower-Ellis & Persson (1980), Verwijst & Nordh (1992), who found that, adding tree height as an independent variable increases the costs and does not improve the accuracy significantly. Röhle et al. (2010) have developed new non-clone-specific empirical models, constructed to estimate wet and oven dry biomass of poplar clones. For poplars and additional short rotation tree species, allometric equations have traditionally been developed for diverse species and hybrids at lower latitudes e.g. (Zianis & Mencuccini 2004; Felix et al. 2008). Various allometric equations have been established to assess standing biomass, including-

$W = aD^b$ (Arevalo et al. 2007; Verwijst & Telenius 1999)………………………….. (1)

$W=a+bD$ (Ballard et al. 2000)……………………………………………………….. (2)

$W=ae^{bD}$ (Volk et al., 2004)…………………………………………………….....(3)

and $W=aD+bD^2$ (Yarie & Mead 1988)……………………………………………..(4)

(where W is the dry weight of the measured tree, a and b are constants, and D is diameter).

The above allometric equations describe biomass estimated in the aboveground portion of the tree, and also biomass in trees is stored at both above and belowground level (Rytter 2012; Zalesny & Bauer 2007). Therefore, allometric equations have been established to assess aboveground and belowground biomass for *Salix spp.* and five other tree species of northern Manitoba in Canada. This model has used stand age as an additional variable due to large variations in age of trees measured (4 – 130 years).

logY= a + b*(logD)+c *(AGE)+ d *(log D* AGE) (Bond-Lamberty et al. 2002)…(5)

(Where D is stem breast height diameter, AGE is stand age, a, b, c and d are regression equation parameters).

Conversely, the above mentioned constants a and b are often limited to the regions and treatments (mainly fertilizers) for which the equation has been derived, therefore may not be suitable for biomass estimation in Czech Republic. The higher latitudes and cool climate in Czech Republic can present unique growing conditions often including low rainfall, cool soils, and short growing seasons compared to conditions observed in lower latitudes. In order to accurately estimate the aboveground biomass in Czech Republic, regional biomass assessments must be undertaken to account for Czech Republic's diverse conditions.

3.2. Assessment of Biomass in SRC plantations

In traditional forestry the yield is normally discussed in terms of volume of timber ($m^3\ ha^{-1}$); however, in SRC it is more concerned with the full tree leaf-off biomass and is usually expressed as dry woody weight per land area (oven dry $t\ ha^{-1}$) or mean annual increment (MAI) expressing the annual growth ($t\ ha^{-1}\ year^{-1}$) as reported in previous literature. Biomass in trees is stored both at above and below ground level (Rytter 2012; Zalesny & Bauer 2007). Numerous tree species have the capacity for SRC plantation while most promising tree species are poplars and willows with high capability of coppicing (Mitchell 1992; Bullard et al. 2002). Sage (1999) has reported *Populus* and *Salix spp.* to be the most common trees, which are cultivated in SRC cultures for bioenergy. Poplars can be grown at many sites such as over-fertilized (former agricultural lands), unfertilized and waste lands etc. The success of the SRC poplar plantations depends on the aboveground and belowground woody biomass production on former arable lands have been studied at many places in the world and more common research focusing on biomass growth has used nursery-raised clones of proven poplar fast growing hybrids including *P. trichocarpa* Torr. & A. Gray x *P. deltoids* W. Bartr.ex Marsh., and *P. balsamifera* L. hybrids (**Table 1**).

Aboveground biomass is mostly harvested under SRC practices, while belowground biomass is equally important as aboveground biomass. In belowground biomass, some sequestrated carbon remains stored in root system including the main large root (tap root) and the smaller fine roots which spread into the surrounding (Singh & Behl 1999; Peichl et al. 2006;Das et al., 2011; Rytter 2012; Don et al. 2012; G. Berhongaray et al. 2013). In poplar SRC, yields could be achieved more than 20 t ha^{-1} $year^{-1}$ when it is planted on the better agricultural lands with frequent irrigation (Scarascia-Mugnozza et al. 1997; Liberloo et al. 2006). In some studies such as Laureysens et al. (2004), Labrecque & Teodorescu (2005) authors have reported satisfactory yields of poplar SRC varying from 10 to 15 t ha^{-1} $year^{-1}$ which can be more realistic. Searle & Malins (2014) have reported overall biomass production of poplar DM falls within the range of 5-10 t ha^{-1} $year^{-1}$.

Table 1: Studies showing aboveground biomass production by poplar trees worldwide (modified Johansson & Karačić 2011 and Bott 2014).

Species	Stand age (years)	Tree weight Kg (dia., mm)	Total Production (tonha^{-1})	Growth Rate (t ha^{-1}yr^{-1})	Trees ha^{-1}	Location	References
P. trichocarpa clone Muhle Larsen	5	nr	62	12.4	nr	Germany	(Hofmann-Schielle et al. 1999)
P. trichocarpa × *P. deltoides* "Boelare"	4	nr	54.2	13.4	nr	England	(Armstrong et al. 1999)
P trichocarpa × *P. deltoides* Clone 11-11	7	13.4 (77)	127.7	18.2	9530	Washington, USA	(DeBell et al. 1996)
P.trichocarpa × *P.deltoides* "Beaupre"	6	9.7	45.9	7.7	4732	Sweden	(Telenius, 1999)
P. Canadadensis "Gelrica"	24	198 (253)	154.8	6.4	782	Sweden	(Persson 1973)
P.trichocarpa	12	-151	55.2	4.6	nr	Norway	(Langhammer and Rep 1967)
P.deltoides Clone I-69	6	70.6 (150)	78.4	13.1	1105	China	(Fang et al. 1999)
Unknown Origin	4	-58	45.2	11.3	nr	Kentucky, USA	(Wittmer & Immel 1976)
P. deltoides × *P. trichocarpa* clone 11-11	4	-97	140.8	35.2	nr	Washington, USA	(Scaracia-Mugnozza et al. 1997)
P.maximowiczii × *P.trichocarpa*	10	13.4 (117)	32	3.2	2388	Maine, USA	(Czapowskyj & Safford 1993)
P.trichocarpa × *P. deltoides* "Siouxland"	7	46.9 (140)	nr	nr	nr	N. Dakota, USA	(Tuskan & Rensema 1992)
P. deltoides	11	167.6 (230)	81.6	7.4	487	Mississippi, USA	(Blackmon et al.

							1979)
P.trichocarpa × *P. deltoides*	12	146.9	163.2	13.6	1110	B.C. Canada	(Zabek Prescott 2006)
P. maximowiczii × *P. trichocarpa*	4	-34	26.1	6.5	nr	Pennsylvania, USA	(Bowersox & Ward 1970)
P. trichocarpa	8	-46	60.8	7.6	nr	Canada	(Heilman & Peabody Jr. 1981)
P. trichocarpa Clone Muhle Larsen	8	-55	49	6.1	nr	Germany	(Bungart & Hüttl 2004)
P. trichocarpa × *P. deltoids* "Boelare"	8	-119	31.8	4	nr	France	(Brahim et al. 2000a)
P. trichocarpa × *P. deltoids* "Beaupre"	9	27.6 (104)	110.4	12.3	4000	France	(Brahim et al. 2000b)
P. trichocarpa × *P. deltoides* "Hazendans"	4	4.6	45.6	11.4	nr	Belgium	(Laureysens et al. 2004)
P. balsamifera × *P. trichocarpa* "Balsam Spire"	5	nr	72.1	14.4	nr	Scotland	(Proe et al. 2002)
P. spp	6	205 (217)	22.1	3.7	1080	Maryland, USA	(Felix et al. 2008)
P. deltoides	9	160 (423)	92.9	10.32	576	India	(Das et al. 2011)
P. balsamifera	nr	278 (250)	142	6.71	510	Sweden	(Johansson & Kracic 2011)
P. balsamifera	nr	170.9 (195)	nr	nr	nr	Alaska, USA	(Yarie et al. 2007)
P. balsamifera	2	1.5 (11.47)	11	5.5	7333	Alaska, USA	Bott 2014
P. nigra	**6**	**nr**	**nr**	**2.6**	**nr**	**Czech Republic**	**(Trnka et al. 2008)**

P. nigra **×** ***P. maximowiczii*** **Maxvier**	**6**	**nr**	**nr**	**11.9**	**nr**	**Czech Republic**	**(Trnka et al. 2008)**
P. nigra **×** ***P. maximowiczii*** **Maxfünf**	**6**	**nr**	**nr**	**13.9**	**nr**	**Czech Republic**	**(Trnka et al. 2008)**
P. maximowiczii **×** ***P. berolinensis*** **Oxford**	**6**	**nr**	**nr**	**10.2**	**nr**	**Czech Republic**	**(Trnka et al. 2008)**

Note: nr indicates information not reported. Information in bold has been added to the original table.

3.3. Factors determining biomass in SRC plantations

Several factors affect biomass (above and belowground) production such as genotypes, tree density, type of soil, nutrients and water availability, climatic environment of a site (light and temperature), phenology of the crop (leaf area development), crop management, rotation length and rotation cycle. In this study only few factors are detailed due to limited time and resources.

3.3.1. Effect of fertilizers on plants growth and SRC plantations

The establishment of new plantations can be improved by fertilizing at the time of planting, to increase early growth rates, allowing the trees to overtop competing from established stands sooner, ultimately reducing the time period between planting and harvesting (Miller 1981). Maximizing growth of energy crops requires minimization of nutrients limitations (Tschaplinski & Norby 1993; Rytter 2002). In SRC plantations, higher biomass productions are generally achieved when fertilization and irrigation is applied (Sannervik et al. 2006). Fertilizers can be used in many forms such as mineral (Nitrogen-N, Phosphorus-P, Potassium-K), organic, and sludge waste etc. DesRochers et al. (2003) have reported that N fertilization reduces both height and basal diameter while, P and K fertilization has no effect on growth, during the 1st year of planting. Similar results are obtained in aspen (*P. tremuloides* Michex.) plantation receiving ammonium nitrate (NH_4NO_3) in an N, P, K and B (Boron) mixed fertilizer without irrigation (DesRochers et al. 2003). N-fertilizer shows negative response because of increased pH (7.7 to 8.1) in the dry conditions that prevail during the first year of growing season and when the root system was not completely developed in first year of plant growth (Van der Stoel et al. 2002; Bennett et al. 2003; Joslin & Wolfe 1998; Iivonen et al. 2001). Volume production of hybrid poplar stands, between 5 and 10 years old range from 5 to 16 m^3 ha^{-1} $year^{-1}$ (Truax et al. 2012; Labrecque & Teodorescu 2005) and values of 16.2 m^3 ha^{-1} $year^{-1}$ have been reported for 6-years old *populus deltoides* (van de Driessche et al. 2008).

In a study, growth response for several poplar clones under different fertilizers combinations of N, NP, and NPKS (S-Sulphur) + Cu (Copper)+ Zn (Zinc) was observed where some poplar clones show non or negative and few of the them show positive growth response (van den Driessche et al. 2008). The effect of N fertilization can change soil properties on mycorrhizal formation which can positively modify or may be useful for short rotation coppice management (Baum et al. 2002). The quantitative effects of fertilization on mycorrhizal colonization might be caused in part by changes in species composition as was observed on pine and spruce and changed the biomass of fine roots (Avis et al. 2008; Lövblad et al. 1995). In fertilizers, N is considered to be the most limiting nutrient to plant growth and produced by many different fungal, bacterial and mycorrhizal mineralizations in most forest ecosystems (Browaldh 1996; Yu et al. 2008) especially in arid and semiarid regions (Meinzer et al. 1988; Franco et al. 1994).

In recent years two problems are more topical, production of solid biofuel from wood and the utilization of ash and organic waste, including waste water sludge. The fertilizing effect of sludge can increase by admixture of wood ash and dolomite. These materials reduce the acidity of the soil and provide additional nutrients. Using dolomite as a limiting material in the amount of 10 t ha^{-1} secures a change in pH of 0.6-1.2 units in peat soil and significant changes in pH (Lazdina et al. 2011). Raw sewage is rich in mineral nutrients needed for plant growth (N, P, K and micro-nutrients). A test of plantation of eucalyptus and poplar irrigated with waste water in India. This research has been done on tree plantations irrigated with waste water indicates that this is potentially both a cost-effective means of treatment and a productive use of waste water, provided in sufficient land available (Braatz et al., 2002). In the Federal Republic of Germany, between 1983 and 1996 soil ecological effects of short-rotation forestry (SRF) were studied on arable land under trial with the nutrients N, P, K, Mg (Magnesium) and Ca (Calcium) (Jug et al. 1999). In a study, Scholz et al. (2011) researchers have compared input of nutrients, herbicides, insecticides, and soil maintenance with annual crops, willows and poplars where they observed after first and second year of SRC poplars perhaps do not need any N fertilization. However, positive production effects were observed in the poplars in the quantities of 150–336 kg N ha^{-1} year^{-1} (Adegbidi et al. 2001; Stanturf et al. 2001) and 50kg N ha^{-1} year^{-1} (Coleman et al. 2004), while in the willow, positive production effects were perceived by quantities of 100kg N ha^{-}1 year^{-1} (Hytönen 1995), 224–336kg N ha^{-1} year^{-1} (Kopp et al. 1996; Adegbidi et al. 2001), and 75–150kg N ha^{-1} year^{-1} (Scholz et al. 2011). Positive and negative impacts of fertilizers on plant growth (during the planting and after the 1st year of plant growth) in tropical and temperate regions are mentioned in detail in **Table 2**.

Table 2: Shows impact of nutrients on biomass production from different sources in different regions.

Study	Study place	Source of nutrients	Results
Use of municipal Waste Water for Forest and Tree irrigation	Near East, Kuwait	Untreated sewage	Used of waste water and Improved the timber production (Armitage n.d.)
Effect of fertilization and irrigation on growth of aspen (*Populus tremuloides* Michx.) seedlings over three growing seasons.	Centre at Drayton Valley, Alta., Canada	Mineral fertilizer (N, P, K and B)	Increased mean height and stem volume with irrigation (DesRochers et al. 2003)
NPK fertilization at planting of their hybrid poplar clones in the boreal region of Alberta	Central Mixedwood Subregion	Mineral fertilizer (N,P and K)	Negative effect of N and no effect of P and K (DesRochers et al. 2006)
Effects of N, NP and NPKS fertilizers applied to four-year old hybrid poplar plantations	Northeastern Alberta	Mineral fertilizer (N, NP and NPKS+Cu+Zn)	NPKS fertilizer decreased height (van den Driessche et al. 2008)
A comparative analysis of potential nitrification and nitrate mobility in forest ecosystem	New Hampshire northern hardwoods forest and other 14th sites	Mineral fertilizer (NH4NO3)	Low N availability disturbed the forest ecosystem produced by litter and humus (Vitousek et al. 1982)
The culture of poplars in eastern North America	North America	Mineral fertilizer N (Urea)	increased mean height and stem volume with irrigation (van den (DesRochers et al. 2003)
Nitrogen fertilization increased cottonwood growth on old-field soil	United States	Mineral fertilizer (NH4NO3)	Increased dbh (Blackmon 1977)
The effects of nitrogen fertilization and soil properties on mycorrhizal formation of *Salix viminalis*	Germany and Sweden	Micorrhizal formation and mineral fertilization	Altered the soil properties in soil and use for SRF (Baum et al. 2002)
Ectomycorrhizal fungi of Scots pine as affected by litter and humus.	Northeastern part of The Netherlands	Litter and Humus	Low nutrient, high organic concentration and pH favored to pine growth, (Baar & Ter Braak 1996)
Effects of ammonium sulphate on the community structure and biomass of ectomycorrhizal fungi in a	Southern Sweden	Mineral fertilizer $\{(NH_4)_2SO_3\}$	The nitrogen treatment reduced the fine-root biomass (to 49% of the control) but did not decrease the mycorrhizal

Norway spruce stand in southern Sweden			frequency (close to 100%) or concentration of ergosterol in fine roots (Karen & Nylund 1997)
Effects of optimal fertilization upon a Norway spruce ectomycorrhizal community		Mineral fertilizer (N)	No significant difference in control as well as treated (Fransson et al. 2000)
Nitrogen mineralization by bacterial-feeding nematodes: Verification and measurement	Agricultural Farming	Bacterial feeding nematodes	N per unit of body weight than larger nematodes and N limited (Ferris et al. 1998)
The effect of water and nitrogen amendments on photosynthesis, leaf demography, and resource-use efficiency in Larrea, a desert evergreen shrub. Oecologia	Jornada Long-Term Eco-logical Research (LTER) site located 40 km NNE of Las Cruces, New Mexico, on a northeast-	Leaf N	Not significantly different on leaves longevity in irrigated and not irrigated plots (Lajtha & Whitford 1989)
Use of waste water sludge and wood ash as fertilizer for Salix cultivation in acid peat soils	Latvia	wood ash and waste water	Changes the pH, reduce the acidity of the soil and provide additional nutrients (Lazdina et al. 2011)
Use of Municipal Waste Water for Forest and Tree Irrigation	India	Municipal waste water	Increased the productivity of crops (Braatz 2002)
Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany	Federal Republic of Germany	Mineral fertilizer (N, P, K, Mg and Ca)	After afforestation all soil properties stabilized for long time (Soil conserved) (Jug et al. 1999)

3.3.2. Leaf area index (LAI) and development

The success of SRC plantations is determined by aboveground woody dry mass (AGWDM) production (harvestable) where plant growth and wood production mainly depend on photosynthetic leaf area and photosynthetic efficiency (Monteith & Moss 1977; Halle et al. 1978, Ceulemans et al. 1996; Broeckx et al. 2012). Cannell et al. (1988) have reported that the photosynthetic leaf area governs the plant's capacity to capture solar radiation, which is linearly related to biomass production.

For biomass production mainly photosynthetic active radiation (PAR) is responsible which are usually evaluated via the LAI (Gardner & Shao 2001; Broeckx et al. 2015). Soltani & Galeshi (2002) have reported LAI to be an important factor in many areas of agronomy, agroforestry and plant production through its influence on light interception, plant growth, weed control, water use and soil erosion. Larson & Isebrands (1972) and Taylor et al. (2001) have stated that LAI represents the total photosynthetically active surface area and correlating with biomass production in poplar SRC plantations. Canopy leaf area serves as the main control over photosynthesis (primary production), radiation penetration, energy exchange, precipitation evapotranspiration, and transpiration rate in forest stands and crops (Broeckx et al. 2012). LAI is a worthy and suitable estimator of woody biomass in SRC culture of poplars (Ceulemans 1990; Barigah et al. 1994; Al Afas et al. 2005; Broeckx et al. 2015, Tripathi et al. 2016). LAI can be measured as one of the main factor for the gain of plant biomass and net primary production for massive plantations and extrapolating temporal and spatial productivity. Maximum leaf area index (LAI_{max}) for short rotation crops are concluded in **Table 3**. The canopy architecture of plant's can be determined by the radiation transfer models and radiation penetration through the canopies (Grantz et al. 1993; Behera et al. 2010).

Measurements of LAI can be therefore used to estimate the standing woody dry mass of SRC cultures and in forest ecosystem. Methods for *in situ* LAI measurement mainly can be categorized into two groups i.e., direct and indirect (Jonckheere et al. 2004; Weiss et al.

2004). Direct LAI measurements in small canopies are rigorous and tedious and closely impossible in large forest canopies (Chen & Black 1992; Jonckheere et al. 2004). Direct (leaf litter collections) or destructive (harvesting of leaves) method uses allometric regression models for estimating LAI (Liberloo et al. 2005; Kurata et al. 2005; Broeckx et al. 2012).

In litter collection direct LAI method, the leaf litters are collected on traps during the leaf-fall time. In this method, the total dry weight of leaves is measured (Liberloo et al. 2005; Tripathi et al. 2016). Leaf harvest direct destructive LAI method is much more labor intensive than direct litterfall collection method (Jonckheere et al. 2004). Indirect nondestructive LAI method, on the other hand estimates LAI using optical modes, for example remote sensing, radiation transmitted through the canopy (i.e. canopy gap fraction), plant canopy analyzer (SunScan-Delta-T Devices, Cambridge, UK and LAI 2000-Li-Cor, Nebraska, USA), hemispherical photography that are based on the tight relationship between canopy light transmittance and LAI (Herbert 1987; Chen et al. 1991; Liu & Pattey 2010; Chen et al. 2006; Broeckx et al. 2015; Tripathi et al. 2016). Halle et al. (1978) have reported tree architecture to determine the orientation and the distribution of the leaves. Hence, tree architecture, categorized by branch morphology, is closely related to stand yield (Ceulemans et al. 1990). According to Halle et al. (1978), Remphrey & Powell (1985), (Ceulemans et al. (1990), and Gielen et al. (2002) branches can be distinguished in two categories in poplar and in some other tree species: (i) proleptic branches (developed from lateral meristems which have been formed during previous growing season (ii) sylleptic branches (develop from lateral meristem during current year). Zeleznik (2007) has observed high leaf area development on sylleptic branches and their high proportion of C allocation to the stem (Scarascia-Mugnozza et al. 1997), a correlation between syllepsis, aboveground biomass production and LAI on the other hand can be expected. Conversely, the relationships between LAI and syllepsis have rarely been examined in high-density plantation with poplar (Broeckx et al. 2012). Due to limited time and resources, architecture of poplar trees under high density SRC management was not observed. **Figure 5** concludes the structural and process determinants shown for different plant genotypes.

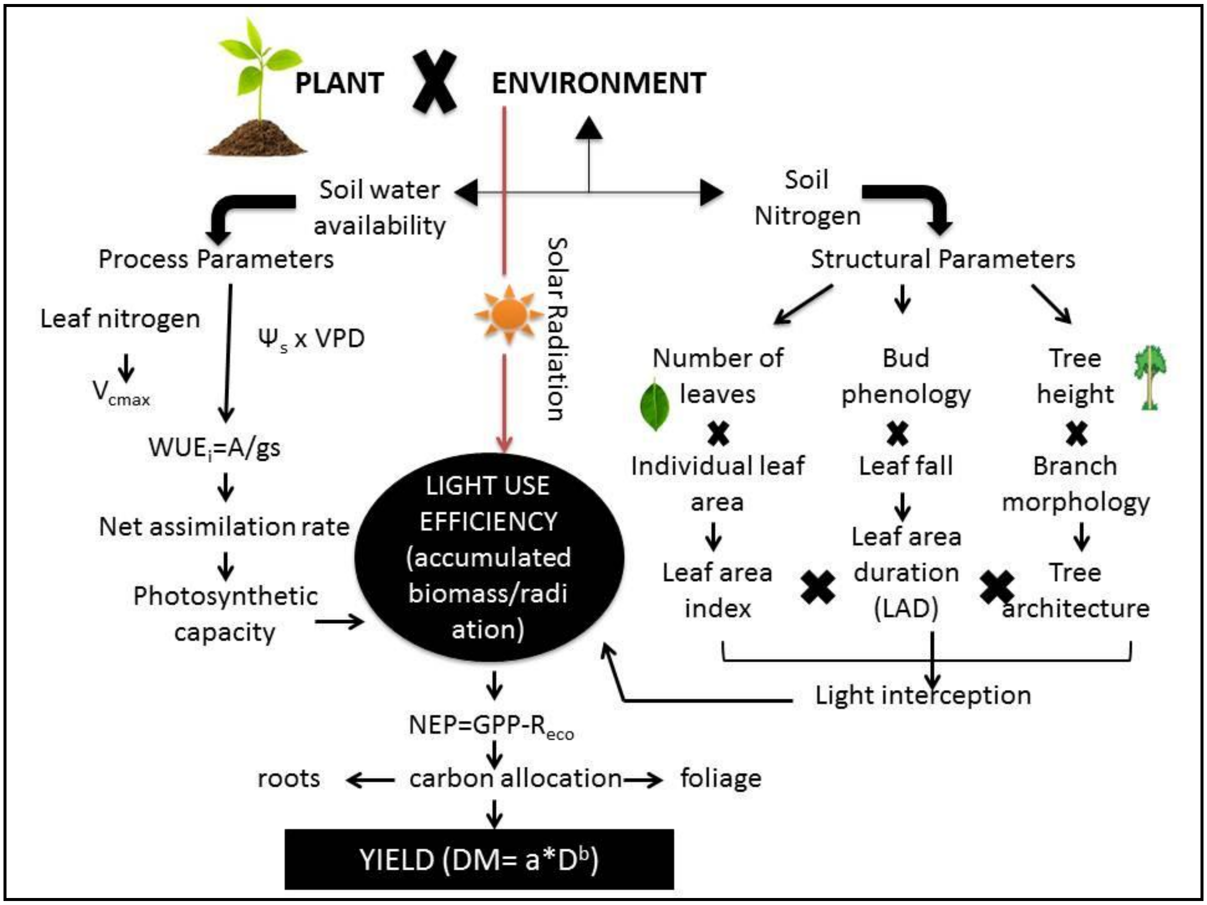

Figure 5: Scheme shows interaction of plant and environment including the factors (growth parameters) for biomass production. Leaf area index (LAI), LAD=leaf area duration, nitrogen (N), A=net assimilation rate, gs=stomatal conductance, V_{cmax}=maximum carboxylation rate (adapted from Broeckx 2013).

Besides the amount of light interception by leaf area, the total duration (which means leaf area duration, LAD) of leaf area are important determinants of growth and productivity. In literature there are several definitions mentioned for duration of growing season; (i) Dowell et al. (2009) have defined the growing season length could be defined as the period of LAD or leaf expansion. (ii) Rousi & Pusenius (2005) defined the limits of the growing season between the time of bud burst and bud set (bud phenology) and (iii) Falge et al. (2002) have defined the period with a net ecosystem exchange (NEE) smaller than zero defines the net carbon uptake period (CUP). UPOV (1981) have mentioned in their guidelines about observation of the growing season based on phenology over the timing of bud burst, more accurately during the first day of the year when the buds were sprouting, with a tip of the small leaves developing out of the bud scales, which couldn't be observed separately. The LAD throughout the growing season can be calculated by summing the total number of leaf duration (from bud burst to completely fallen of the leaves), integrating the absolute LAI and the growing season length (Ceulemans & Deraedt 1999; Dowell et al. 2009; Broeckx et al. 2012). Therefore to check the overall productivity, determinants of poplar SRC by light interception on leaf area and LAI are studied in the thesis.

3.3.3. Radiation use efficiency (RUE)

RUE can be another determinant which is directly linked to plant growth and biomass. Productivity of the crops and growth are demarcated by light capture which is the quantity of photosynthetic active radiation (PAR) and by multiple efficiency factors (Monteith & Moss 1977; Biscoe & Gallagher 1977). Apart from nutrients and LAI, RUE is maximizing the productivity in a short amount of time and this agricultural technique can be applied on forest crops. (Gifford et al. 1984), Linder (1985) and Stape et al. (2004) have reported biomass production of plants to be dependent on the availability and the intercepted radiation by the canopy which is used for converting CO_2 into new biomass. This intercepted light may depend on the plant cover mostly LAI, the crop's capacity to intercept radiation is decided by its photosynthetic area, generally evaluated via the LAI which is linearly related to the biomass production in poplar and willow plantations (Taylor et al. 2003). RUE determines the biomass or crop yield as indirect for both woody (tree) and herbaceous (cereal) crops such as poplar, willow, wheat and barley etc. (Cannel et al. 1988; Sinclair & Horie 1989). Numerous studies have confirmed that the range in annual aboveground net primary product (ANPP) observed for monoculture forests is positively and linearly correlated to the annual quantity of intercepted PAR (Grace et al. 2007; Dalla Tea & Jokela 1994). For instance, 90% of the disparity in ANPP and annual stem-wood growth of loblolly pine and slash pine plantations were explained by intercepted PAR (Grace et al. 2007; Dalla Tea & Jokela 1994). ANPP enumerates the stability between gross photosynthetic production of carbohydrates and carbon lost over cellular respiration in aboveground plant parts. There are several factors such as water use efficiency (Kemanian 2009), low temperature (Goyne et al. 1993) and drought (Jamieson et al. 1995) which may affect RUE for total biomass production including above and belowground biomass. It may vary with genotypes and crop management such as coppice and uncoppiced and their growth stages (Ceulemans et al. 1996; Broeckx et al. 2015). Intercepted PAR assesses the entire quantity of energy absorbed by plant canopies for photosynthesis, and delineation for the effects of total leaf area display and canopy architecture (Zhi et al. 2014). Grace et al. (1988) have stated to estimate ANPP for agricultural crops and monoculture forests using ground measurements of Intercepted PAR and integrated measurements of incident PAR.

In trees, aboveground RUE values are usually lying between 1.3 and 1.9 g MJ^{-1}, where average RUE values were found to be 1.5 g MJ^{-1} for poplar in Pennsylvania and Wisconsin, USA (Kiniry et al. 1989; Landsberg & Wright 1989). Maximum RUE values of 1.7-2.7 g MJ^{-1} was seen for fast growing tropical trees, including *Eucalyptus camaldulensis* (Harrington et al. 1995). Conversely, RUE values of 2.4-3.4 g MJ^{-1} were reported for intensive managed willow and poplar in Scotland (Cannel et al. 1988). Kiniry et al. (1998) have reported RUE values for *Juniperus virginiana* (1.60 g MJ^{-1} intercepted PAR) and *Prosopis glandulosa* (1.61 intercepted g MJ^{-1} PAR) to allow better prediction of their growth in Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMA NAC) model. For temperate-evergreen-conifer forests stands in Montana RUE values were 0.2 g MJ^{-1} in ponderosa pine (Pinus ponderosa Dougl.) and 0.9 g MJ^{-1} in Douglas-fir (*Pseudotsuga menziesii* Mirb.) stands in the United States (Gower et al. 1999). RUE values of 0.46 g MJ^{-1} and 0.49 g MJ^{-1} have been observed for twenty one year old slash pine and thirteen year old loblolly pine stands, respectively (Gholz et al. 1991; DeLucia et al. 2002). RUE values can be strong for evergreen conifer species and fast growing tree species across a range in soil fertility, irrigation and site conditions (Dalla-Tea and Jokela 1991; Ceulemans et al. 1996). RUE values for short rotation woody crops for both uncoppiced and coppiced management systems at different places with different fertilizer treatments are concluded in **Table 3**.

Table 3: Maximum leaf area index (LAI_{max}) and radiation use efficiency (RUE) of accumulated photosynthetic radiation (APAR) into aboveground dries matter (and/or total dry mass) for high density, intensively managed eucalypt, poplar and willow stands from available literature data. The RUE is expressed in g MJ^{-1}. Equivalent values of energy use efficiency based on intercepted total solar radiation will be approximately half the RUE values given. Specifications on the experimental set-up (such as age of the stand, place, and length of the growing season) have also been indicated when available (adapted from Ceulemans et al. 1996).

Treatment	Age (years)	Locality	Growing season (months)	LAI_{max} ($m^2.m^{-2}$)	RUE (g MJ^{-1})	References
Eucalyptus sp.						
Irrigated, fertilized	3	Central Portugal	12	3.8	1.6	Pereira et al. 1992
Irrigated	3	Central Portugal	12	3	1.56	Pereira et al. 1992
Fertilized	3	Central Portugal	12	2.8	1.42	Pereira et al. 1992
Control	3	Central Portugal	12	2.3	1.36	Pereira et al. 1992
Fertilized	2-10	Victoria, Austrailia	12	0.8-6	0.9	Linder1985
Fertilized, weed controlled	1-3	Tasmania, Southern Austrailia	12	4 - 6	0.86	Turnbull et al. 1994
Populus sp.						
Not irrigated, not fertilized	5	Flanders, Belgium	6	4	0.9-1.9	Lemueur & Impens1981
Five clones, irrigated	2	Flanders, Belgium	6	6.1 - 9.4	0.72-1.10	Impens et al. 1990
Irrigated	1	Scotland, U.K.	6.5	3.5	2.11	Cannell 1989
Fertilized three clones					3.14 (total)	
Containerized plants, fertilized	1	Scotland, U.K.	6.5	5.1 - 5.6	1.18	Milne et al. 1992
Different treatments	1	Pennsylvania, U.S.A	6	6	0.32	Landesberg & Wright1989
Different treatments	2	Pennsylvania, U.S.A	6	7	1.4	Landesberg & Wright1989
irrigated, fertlized	1-3	Wisconsin, U.S.A	5	8	1.16-1.28	Landesberg & Wright1989
Salix sp.						

Control	1	Scotland, U.K.	6.5	-	2.11	Cannell 1989
Containerized plants, irrigated	1	Scotland, U.K.	6.5	4.5	2.94	Cannell 1989
Fertilized					3.59 (total)	
Irrigated, fertilized	4	Sweden	7	5	1.66	Eckersten & Nilsson 1990
Irrigated, fertilized	5	Sweden	7.5	6.6	2.48	Eckersten & Nilsson 1990
Irrigated, fertilized	6	Sweden	7.5	5.9	1.93	Eckersten & Nilsson 1990
Irrigated, fertilized	1 (coppiced)	Scotland, U.K.	6	2.4	0.99	Cannell et al. 1987
Irrigate, fertilized	2 (coppiced)	Scotland, U.K.	6	4.5	1.38	Cannell et al. 1987

Chapter 4

4. Materials and methods

4.1. Experimental location

The experimental site for this study was located at Domanínek, Czech Republic (49°31´N, 16°14´E) with poplar plantations. This research site is part of the Bystřice nad Pernštejnem city in the Czech-Moravian Highlands at an altitude of 530 m above the sea level (a.s.l.). This area is suitable for agricultural crops such as potatoes and cereals (Trnka et al. 2008).

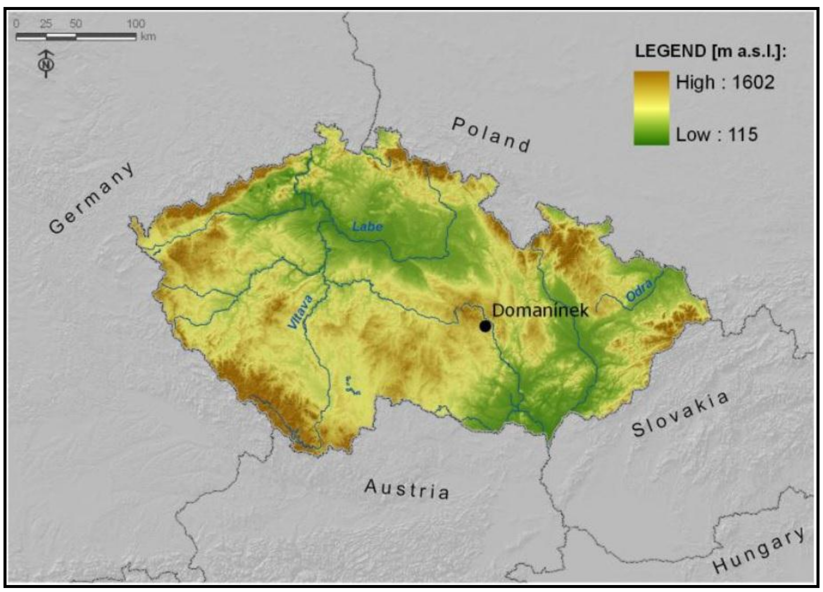

Figure 6: Geographical location of the research site Domanínek, Czech Republic (Fischer 2012).

4.1.1. Poplar plantations

Plantations were established at two adjacent places in April 2001 and 2002 with total area of 1.5 and 2.85 ha, respectively in high density (9,216 trees ha^{-1}) to test the performance of poplar clone J-105 (*Populus nigra* L. x *P. Maximowiczii* H.) on former arable land, previously cropped with predominantly cereals and potatoes in Domanínek (Trnka et al. 2008, Tripathi et al. 2012; Fischer et al. 2013). For planting, hardwood cuttings were used in double-row design model (Swedish model), where inter row distances was 2.5 m spacing and within row was 0.7 m (**Figure 7**).

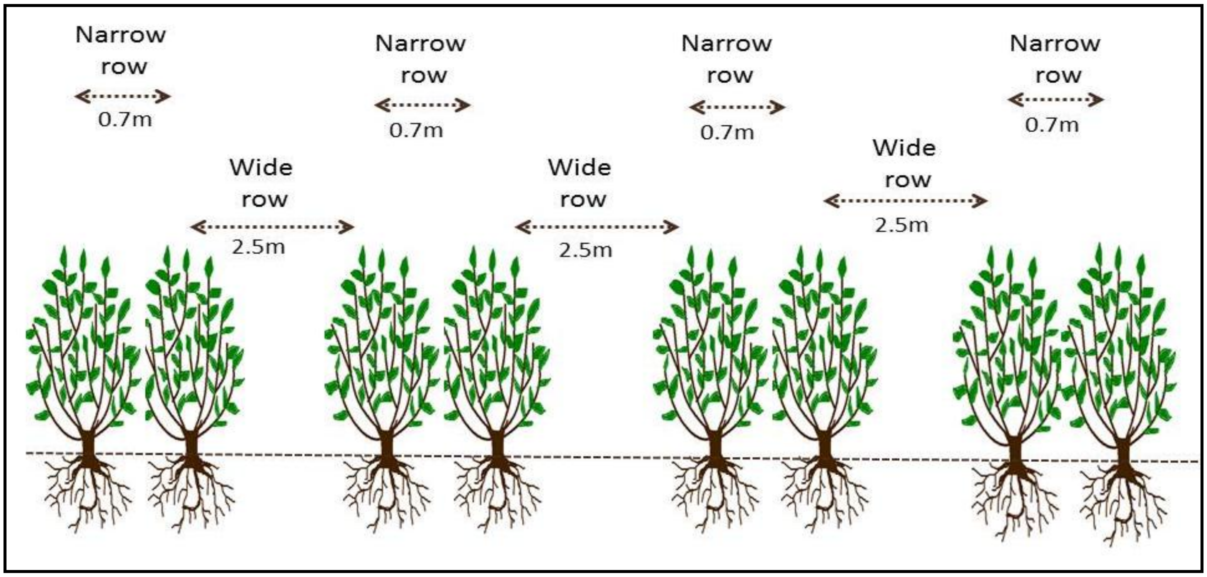

Figure 7: Sketch of double row poplar planting system under short rotation coppice (SRC) management in the present research study at Domanínek.

The plantations were established without any treatments such as irrigation, fertilization and herbicide treatments (except the local application of Roundup on the most vigorous and tenacious weeds) (Fischer 2012). Following which mechanical weeding was performed two times per growing season till the increased tree height and canopy cover in 2005 (Fischer 2012). The main competitive weed species were *Cirsium arvense, Rumex crispus, Rumex obtusifolius, Artemisa vulgaris, Tanacetum vulgare, Elytrigia repens and Arrhenatherum elatius* (Fischer 2012).

After eight years (total age of trees) of plant growth, the plantations were harvested above 15-20 cm from base in winter 2008/2009 (established in April 2001) and 2009/2010 (established in April 2002). Established plantations were standing with single stem (uncoppiced) after the first harvest plantations were converted into multi-stem (coppice). In this thesis, poplar short rotation woody coppice plantations are mentioned as SRWC1 (coppice established in 2009) and SRWC2 (coppice established in 2010), respectively. In spring 2009 (at the beginning of second rotation) SRWC1 was divided into four randomized blocks and treated with three different fertilizers such as mineral [Nitrogen (N), Phosphorus (P), and Potassium (K)], sewage sludge and ash, lime and control (without any treatment of fertilizer). The dose of mineral fertilizer (N 305 kg ha^{-1}, P 154 kg ha^{-1} and K 291 kg ha^{-1}), sewage sludge (21,000 kg ha^{-1} of raw sludge containing 4200 kg ha^{-1} of dry matter) and ash (1000 kg ha^{-1}), lime (5 ton ha^{-1}) and control with natural nutrients content only (deposition and leaves mineralization). Mineral fertilizer used was urea (N 46%), amofos (P 52%) and potassium salt (K 58%). Lime is source of Ca and Mg used to improve the soil acidity (pH) (Tripathi et al. 2012). In the plantation SRWC2, no further (at beginning of second rotation) external fertilizer treatment was applied. Both (SRWC1 and SRWC2) plantations are shown in **Figure 8**.

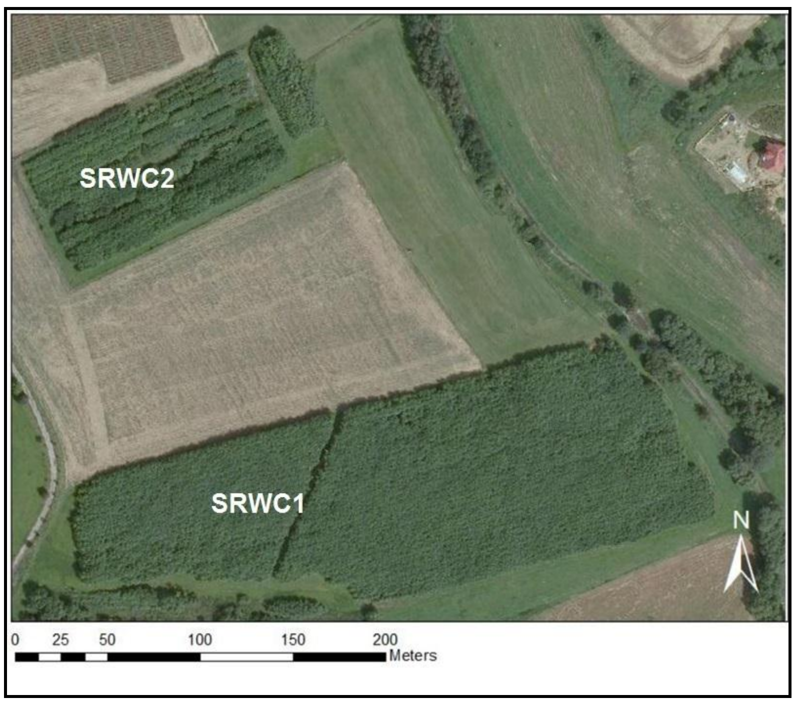

Figure 8: Aerial image of poplar plantations SRWC1 and SRWC2 (described in methodology) in Domanínek. The plantation with clonal experiment is described by Trnka et al. (2008) and Fischer et al. (2013).

4.1.2. Climatic condition at research site

Climatic condition of the experimental site was cool and relatively wet moderate which is typical climate for this part of Central Europe with associating continental and naval influences and it is located on a slight slope (3^{o}). The experimental site climate is suitable for short rotation coppice (SRC) based on *Populus* species (Havlíčková et al., 2006; Trnka et al. 2008). Meteorological parameters were obtained from the closest weather station Bystřice nad Pernštejnem (49° 32´ N, 16° 16´ E and altitude 560 m a.s.l.) of the Czech Hydrometeorological Institute (CHMI), which is about 1 km far from the experimental site in at Domanínek (Czech Republic). From 2001 to 2014 mean and dynamics of air temperature and precipitation are shown in **Table 4** and **Figure 9**, respectively.

Table 4: Climatic conditions at Domanínek research site (table modified from Trnka Et Al. 2008; Tripathi et al. 2012; Fischer et al. 2013).

Parameter	Units	Jan-Dec	Apr-Oct	May-July	Nov-March
Mean air temperature (1961-1990)	^{O}C	6.6	12.7	15.3	-2.7
Mean air temperature (2001-2014)	^{O}C	7.6	13..0	15	-0.5
Precipitation (1961-1990)	mm	578	392.9	210.7	185.2
Precipitation (2001-2014)	mm	606	411	215	194

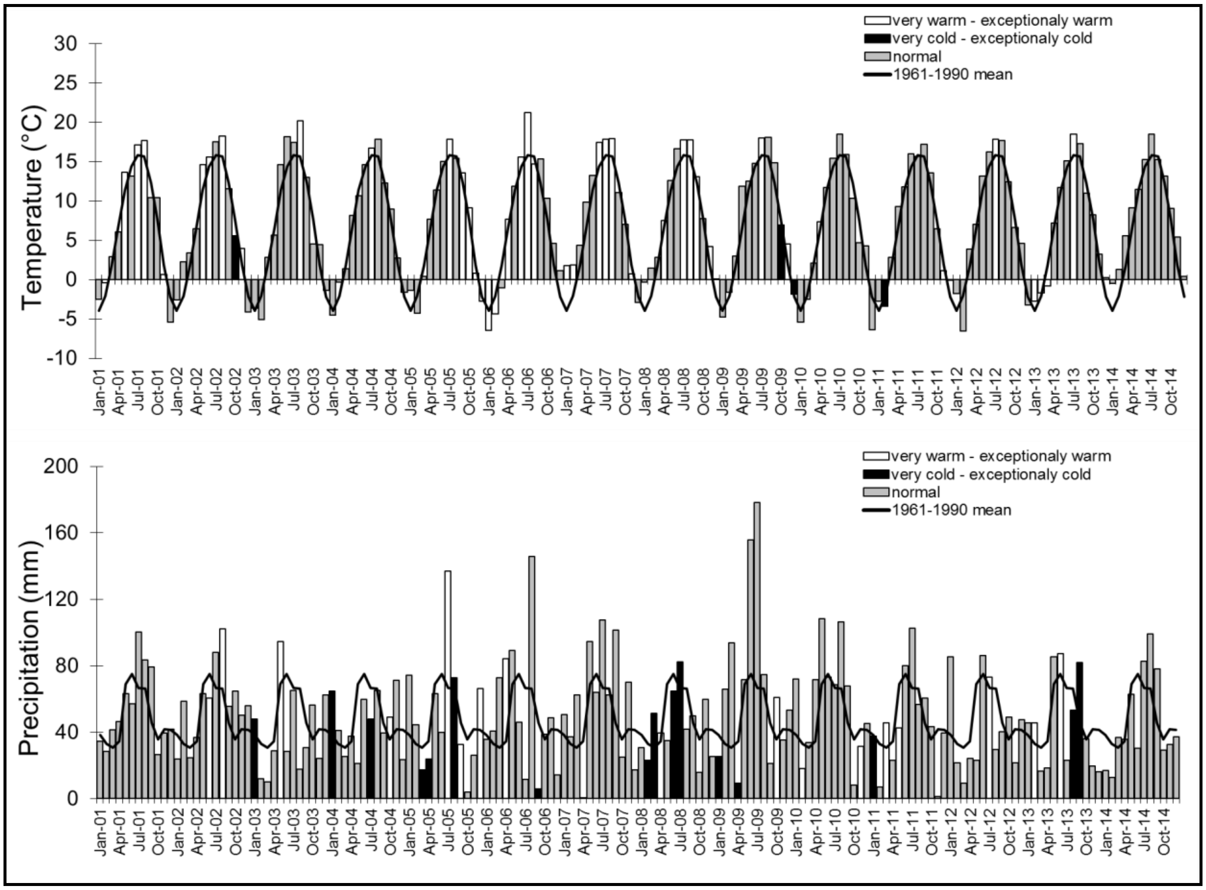

Figure 9: Time course of mean monthly air temperatures (°C) and monthly total precipitation (mm) from 2001–2014 (from establishment of plantations to the experimental period) in comparison with the 1961–1990 periods (represented as a black solid line). The thresholds of World Meteorological Organization for assessment of the meteorological conditions were used (Kožnarová and Klabzuba 2002 and modified from Fischer 2012).

4.1.3. Soil type

Soil sampling was done prior to planting the hardwood cuttings in 2001 and 2002 (**Table 5**). Soil types at the locality are typical of the broader region with deep luvic Cambisol influenced by gleyic processes and with a limited amount of gravels in the soil profile. The research site is highly suitable for poplar planting due to deep soil profile (Trnka et al. 2008). Except for the first soil sampling, usually soil sampling was done in every mid-July from 2007 to 2014. Samples were collected by soil sampler (~1 m depth with top view) and also dug area was ~0.5 m^2 in both poplar plantations. Soil samples were divided to into three depths (~0.1, ~0.4 and ~0.7 m), collected into plastic bags and immediately put into movable freezer, after which they were sent to the laboratory for soil physical, chemical and mechanical property analysis.

Table 5: Analysis of the soil characteristics at the experimental place in Domanínek , where the fraction of sand (0.05–2 mm), silt (0.05–0.002 mm), clay (< 0.002 mm); organic matter and total nitrogen are expressed in terms of weight fraction (wt %). The concentration of available nutrients was determined by Mehlich III method (adapted from Trnka et al. 2008; Fischer 2012).

Soil characteristics					
Component	Units	Depth (cm)			
		0-24	24-66	66-94	94-130+
Silt	wt %	50	46.1	38.7	19.6
Clay	wt %	15.8	26.3	18.6	13.3
Bulk density	g/cm3	1.55	1.64	1.59	1.64
Organic matter	wt %	2.65	0.28	0.14	0.14
Total nitrogen	wt %	0.16	<0.05	<0.05	<0.05
pH (KCl)		5.9	5.4	4	3.4
Available P	mg/kg	148	1.3	0.9	24
Available K	mg/kg	151	91	62	76
Available Mg	mg/kg	143	230	278	291
Available Ca	mg/kg	1230	1353	748	652

4.2. Measurements and data processing

4.2.1. Developing allometric equations for aboveground woody dry biomass on fertilized and non-fertilized former arable lands

In winter 2010/2011, a total sixty-five trees were harvested from SRWC1 (coppicing established year 2009). Forty-five trees were harvested from treatments (mineral, sludge & ash and lime) and twenty trees from control. In winter 2011/2012, total twenty five trees were harvested from SRWC2 (coppicing established year 2010). Tree’s selection was based on DBH (diameter at breast height 1.3 m) which was ranging from 10-50 mm. Tree’s DBH were measured by using digital caliper (150 mm digital caliper DC04150). After the successful harvesting of trees, length of felled trees was measured using a measuring tape and number of branches were counted over 10 mm diameter girth. Whole tree was divided into two parts, stems and branches for chipping, in order to determine the woody dry mass (DM). Samples were taken from all treatments (mineral, sludge & ash, lime) including control (in SRWC1 and also from SRWC2 (no treatments), respectively. These samples were converted into wood chips (~0.75 dm^3) which represented a mixture of whole tree branches and stem parts, which was weighed in fresh state on an analytical balance (BS600H, 600g/0.01g accuracy of balance was 0.01 g). Overall, six random samples (three for stem and three for branches) were selected from each treatments including control in SRWC1 and no treatments in SRWC2. The biomass samples from SRWC1 in winter 2010/2011 and SRWC2 in winter 2011/2012 were stored in aluminum boxes and subsequently dried in ventilated oven at 105 ^{o}C until constant weight was achieved (Ketterings et al. 2001; Basuki et al. 2009). Allometric equations were developed for relationships between DBH (1.3 m above the ground diameter breast height), total tree height against amounts taken (dry weight) using the scatter plots as a best fit trend lines were applied (exponential/power function) using MS excel 2010 software. Fore aboveground standing woody DM, allometric equations (**Table 6 & 7**) and trend lines (**Figure 10 & 11**) for both SRWC1 and SRWC2, was obtained.

4.2.2. Developing allometric equations for belowground woody dry biomass on former arable lands

For belowground woody dry mass (BWDM) determination, allometric equations were developed for SRWC2 plantation (total age of stumps were between twelve to thirteen years after the establishment in April 2002 and age of stems were between four to five after the coppice establishment in winter harvest 2009/2010). In August 2014, total seven trees were selected of different stem DBH (diameter at breast height 1.3 m from 2.5 to 6 cm and basal area ranging from 10 to 135 cm^2) and DBH were measured by using digital caliper (150 mm digital caliper DC04150). Those seven selected trees were felled at 22 cm above the soil surface, after which excavation was performed to develop an allometric equation for BGWDM. The root systems of seven selected trees were completely excavated from the

Voronoi polygon method which confined by an area of 0.7 m x 1.6 m (planting distance within the rows × sum of half inter-row distances, Berhongaray 2014). All roots (coarse roots-Cr, Ø > 5 mm) within this 1.12 m^2 area were collected, assuming that roots from nearby trees within the sampled area compensated for roots of excavated tree growing outside the sampled area. Excavation depth was limited to 60 cm, as very few roots were observed under 60 cm (eye observation). Roots that were inserted below 60 cm during the excavation were not recovered by complete excavation, but they were extrapolated up to 100 cm rather than pulled out. Cr was collected separately of 0-60 cm soil layers from both the narrow and the wide inter-rows. All Cr were stored in paper bags and then put into ventilated oven for drying at 75^{o}C until the constant weight was achieved to determine the BGWDM. Amounts taken (dry weight of Cr) on the collected material were used to correlate the standing BGWDM measurements with the dry weights. Allometric equations were developed for relationships between basal area of per stump against dry weight of Cr using the scatter plots as a best fit trend lines (linear and nonlinear) were applied (power equation, **Figure 12**) in excel 2010.

4.2.3. Dynamics of woody dry biomass

4.2.3.1. Dynamics of aboveground woody dry mass

For estimation of aboveground woody dry mass (AGWDM) in both plantations SRWC1 and SRWC2, inventory was performed and followed by allometric equations (**Table 6 & 7,** respectively**).** In this thesis, annual AGWDM and cumulative AGWDM were estimated over four years from 2011 to 2014 in SRWC1 (growing season GS3 to GS6) and SRWC2 (growing season GS2 to GS5), respectively. During inventory shoot per stool ratio and survival or mortality rate were also estimated in the both plantations in SRWC1 (growing season GS3 to GS6) and SRWC2 (growing season GS2 to GS5). Inventory was performed every year at the end or before the start of the next growing season (in winter) to estimate the annual AGWDM, cumulative AGWDM, shoot per stool and mortality or survival rate in both plantations.

For inventory in both plantations double row design trees were divided into two stumps, left and right. In SRWC1, a total of fourteen rows were selected in all treatments including the control (three in mineral, three in sludge & ash, three in lime and five in control). Total 784 trees were selected from all treatments including control (168 in mineral, 168 in sludge & ash, 168 in lime and 280 trees in control). In SRWC2, total six rows were selected where 624 trees (each row 104 trees) were marked for inventory in each year. In the inventory, all shoots per stump DBH (diameter at breast height 1.3 m) were measured by using digital calipers in the selected trees and also counted the number of mortal trees to estimate the survival or mortality rate per row or plot. Allometric equations were used to scale-up AGWDM based on DBH and by using specific planting density mortality or survival rate ha^{-1} (Fischer 2012; Tripathi et al. 2012). Inventory was repeated every year almost at the same time (after or before the start of the new growing season during winter) in both plantations.

4.2.3.2. Belowground woody dry mass

For estimation of belowground woody dry mass (BGWDM) SRWC2 plantation was considered where inventory data (see details in chapter 4 section 4.2.3.1) were used from 2011 to 2014 and followed by developing the allometric equation (**Figure 12b**). The developed allometric equation was then used to estimate the annual average BGWDM per stump. By using the data from the stem diameter inventory in each growing season, the relationship between basal area of each stump and total BGWDM was established (Berhongaray et al. 2015; Tripathi et al. 2014). Inventory was repeated every year almost at the same time (details mentioned in chapter 4 section 4.2.3.1).

4.2.4. Evaluation of leaf area index (LAI) including leaf area development

4.2.4.1. Measurement of direct (non-destructive-litterfall) LAI

Direct LAI was measured in SRWC2 plantation where three litter traps with 3 m^2 known surface area were installed on the ground. Litter traps were located at three different places in the middle of inter-rows nearest to the where planned indirect LAI measurements done by the

SunScan Plant Canopy Analyzer (Delta-T Devices, Cambridge, UK). During the fall season (autumn) litterfall were collected in already installed litter traps for the measurement period 2009 (Fishcer 2012) and 2012 (in the current thesis and see details in Tripathi et al. 2016). The contents of the traps represent the average volume of leaves falling in the stand. Usually, litterfall collection was done for five to seven times in a year without loss of original weight. Collected leaves from litter traps were put into three different paper bags and oven dried at 70°C until a constant weight was achieved. From each bag a representative sample of leaves (~30 leaves) were taken and these leaves were spread on a rectangle white board with a known board dimension (length 1 m ×width 0.5 m). Digitally (photographs) leaves were captured by a digital camera Canon power shot A3100 (4X optical zoom, 12.1 megapixel, Malaysia). Photographs were saved in high-quality JPEG file format and stored on a secure digital (SD) memory card. The images were analyzed using the ImageJ 1.4.1 software (Rasband 2012). According to Glozer (2008) protocol, all the color photographs were converted into B & W (black and white), as the black area was required to be analyzed in line with the software. This method was described to measure the leaf area by using an image histogram and photographic software tools (see details in Tripathi et al. 2016).

4.2.4.2. Indirect LAI measurements through a Plant Canopy Analyzer

Indirect LAI was measured in SRWC2 plantation at three places close to litterfall collections. For the indirect LAI measurement SunScan Plant Canopy Analyzer (Delta-T Devices, Cambridge, UK) was used. This indirect LAI technique is based on optical measurements where there is simultaneous measure of the photosynthetic active radiation (PAR) in waveband 400-700 nm above and the transmitted below plant canopy. The incident PAR was measured by the Beam Fraction Sensor (BFS), which incorporates with SunScan probe which is always under the canopy. The BFS could be connected by a 50 m long cable or radio link (435 MHz type SS1-RL4). SunScan probe is the light sensitive device which is 1 m long that contains sixty-four photodiodes. The probe handle contains electronics and sends output into PDA via the RS232 link. More details of SunScan Plant Canopy Analyzer are mentioned in SunScan Canopy Analysis System, SS1 user manual v2.0 (Delta-T Devices

Ltd.). Measurements were usually done on weekly and biweekly basis during growing season (mid-April to mid-October) over four growing seasons (GS1 to GS4) from 2010 to 2013 (Tripathi et al. 2016). Indirect LAI measurements using SunScan Plant Canopy Analyzer, data were collected approximately 30 times (readings) from each row and this was divided into inter-row and within row in the double row design plantation (see details in chapter 4 section 4.1.1). The measurements were done either early in the morning or late in the afternoon because of sun position (Potter et al. 1996). Measured values were stored by SunScan Plant Canopy Analyzer, which are considered to be the plant area index (PAI) during the whole growing season measurements. Therefore, at the end of the growing season (completely fallen leaves from plant canopy); the same measurement was carried out by the SunScan Plant Canopy Analyzer to determine the wood area index (WAI). The WAI was subsequently deducted from the measured value (PAI), and finally the LAI was obtained (Tripathi et al. 2016). For gap-filling, interpolation was used for the weekly LAI data with help of daily mean air temperature and obtained daily values of LAI (Linderson et al. 2007).

4.2.4.3. Estimation of leaf area duration (LAD)

For the plantation SRWC2, LAD was calculated by relative air temperature (above $5^{o}C$) during growing season (mid-April to mid-October) over four growing season (GS1 to GS4) from 2010 to 2013. LAD counted the total number of days from bud burst to completely fallen leaves to the ground (Linderson et al. 2007; Broeckx et al. 2012b).

4.2.5. Estimation of radiation use efficiency (RUE)

The RUE was calculated for the SRWC2 plantation using equation 6 where RUE is the ratio between produced dry mass (g DM m^{-2}) and the total amount of accumulated active photosynthetic active radiation (APAR, MJ m^{-2}) for annual production in plants (Cannel et al. 1988; Bullard et al. 2002; Linderson et al. 2007).

$$RUE = \Delta W_s / APAR \quad \ldots\ldots (6)$$

where ΔW_s= total dry mass production (g DM m^{-2})

APAR was evaluated at stand level using Beers Law:

$$APAR = PAR_{above}(1-e^{-kLAI}) \qquad (7)$$

where PAR_{above} correlates to cumulated PAR above canopy in growing season, k= light extinction coefficient and LAI= daily leaf area index. For fast growing trees k is estimated to vary between 0.4-0.6 (Eckerston 1984; Linderson et al. 2007). In the present study k value is 0.5 for poplar which is taken from (Eckersten, 1984).

At the research site in Domanínek close to plantation in an open area the incoming short-wave radiation (solar radiation) was continuously monitored during experimental period from 2010 to 2013 by using global radiation sensor EMS 11 (EMS Brno, Czech Republic). This global radiation was converted into photosynthetic active radiation (PAR) according to Linderson (2007) PAR is ~0.5 of global radiation. Daily LAI was extrapolated from weekly and biweekly measurements using SunScan Plant canopy Analyzer (details are mentioned in chapter 4 section 4.2.4.2) and APAR was calculated by using equation 7.

4.3. Statistical analysis

Firstly, Microsoft Excel 2010 (Microsoft office 2010, USA) was used to derive power allometric equations to estimate AGWDM in both plantations (SRWC1 and SRWC2) and derived power and linear allometric equations to estimate BGWDM in SRWC2. Secondly, for plantation SRWC1, statistical software R was used to check the normality (Q-Q and Shaipro-Wilk test), basic statistics (mean, standard deviation, standard error and confidence interval) and two way repeated analysis of variance (ANOVA) and followed by post-hoc Tukey test (HSD, $p < 0.05$) to check differences in survival rate, shoot per stool and AGWDM (annual and total) among the fertilizers and within year in plantation SRWC1. This analysis was also confirmed in SPSS® (IBM Corp., SPSS 16. statistics for Windows, Armonk, NY) where post-hoc Tukey (HSD) and Fisher (LSD, $p < 0.05$) both tests were done to check the high and low significant differences. For plantation SRWC2, normality test (Q-Q and Shaipro-Wilk), basic statistics (mean, standard deviation, standard error and confidence interval) and one way repeated

ANOVA and followed by post-hoc Tukey test (HSD) was done to check differences in survival rate, shoot per stool, AGWDM and BGWDM among the years from 2011 to 2014. SigmaPlot® verson 11.0. (Systat Software, San Jose, CA, USA) was used to plot the graphs and determined the correlation between indirect LAI (measured by SunScan Plant Canopy Analyzer) vs. direct LAI (measured by littefall collection). Coefficient of determination (R^2) was calculated to fit a slope of the linear regression. For a correlation matrix (annual average LAI vs. annual AGWDM, maximum LAI vs. annual AGWDM, LAD vs. annual AGWDM, RUE vs. annual AGWDM, RUE vs. LAI_{max} and RUE vs. LAD). Pearson's correlation coefficients in SPSS® (IBM Corp., SPSS 16. statistics for Windows, Armonk, NY) and graphs were made in SigmaPlot® verson 11.0 (Systat Software, San Jose, CA, USA).

Chapter 5

5. Results and discussion

5.1. Allometric relationships

5.1.1. Allometric relationships for the allocation of aboveground woody dry mass

For plantation SRWC1, relationship between stem diameters (DBH) vs. weight of dry branches (kg), weight of dry stems, total weight of dry tree (branch+stem) and height of tree (m) was determined. Allometric equations are mentioned in **Table 6** and its relationships with power fitting curve are shown in **Figure 10**. For allocation of biomass on over fertilized or former arable land with fertilizer treatments including control, relationship of all allometric equations are very strong where R^2 values were ~ 1, varying from 0.91 to 0.99 and there is no significant differences observed in R^2 values of any of the treatments and control, respectively.

Table 6: Shows allometric power functions to estimate dry mass (DM) for branch, stem and branch+stem (total aboveground woody) in fertlizer treatments including control for poplar clone J-105 after two years of plant growth in coppice (SRWC1).

		Branch (DM in kg)		Stem (DM in kg)		Total aboveground (DM in kg)		Tree height (m)	
Treatments	Total tree (n)	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
Mineral	15	$y=6.24E\text{-}05x^{2.42}$	0.95	$y=6.21E\text{-}04\,x^{2.18}$	0.995	$y = 6.21E\text{-}04x^{2.18}$	0.99	$y = 6.21E\text{-}04x^{2.18}$	0.99
Sewage sludge & ash	15	$y=3.63E\text{-}05x^{2.60}$	0.91	$y=8.20E\text{-}04\,x^{2.11}$	0.99	$y = 8.20E\text{-}04x^{2.11}$	0.98	$y = 8.20E\text{-}04x^{2.11}$	0.98
Lime	15	$y=1.87E\text{-}05x^{2.74}$	0.94	$y=4.51E\text{-}04\,x^{2.27}$	0.99	$y= 4.51E\text{-}04x^{2.274}$	0.99	$y = 4.51E\text{-}04x^{2.274}$	0.99
Control	20	$y=4.83E\text{-}05x^{2.50}$	0.94	$y=6.32E\text{-}04\,x^{2.17}$	0.99	$y =6.32E\text{-}04x^{2.17}$	0.99	$y =6.32E\text{-}04x^{2.17}$	0.99
All treatments	65	$y=3.96E\text{-}05x^{2.55}$	0.93	$y=6.12E\text{-}04\,x^{2.19}$	0.99	$y = 6.12E\text{-}04x^{2.19}$	0.99	$y = 6.12E\text{-}04x^{2.19}$	0.99

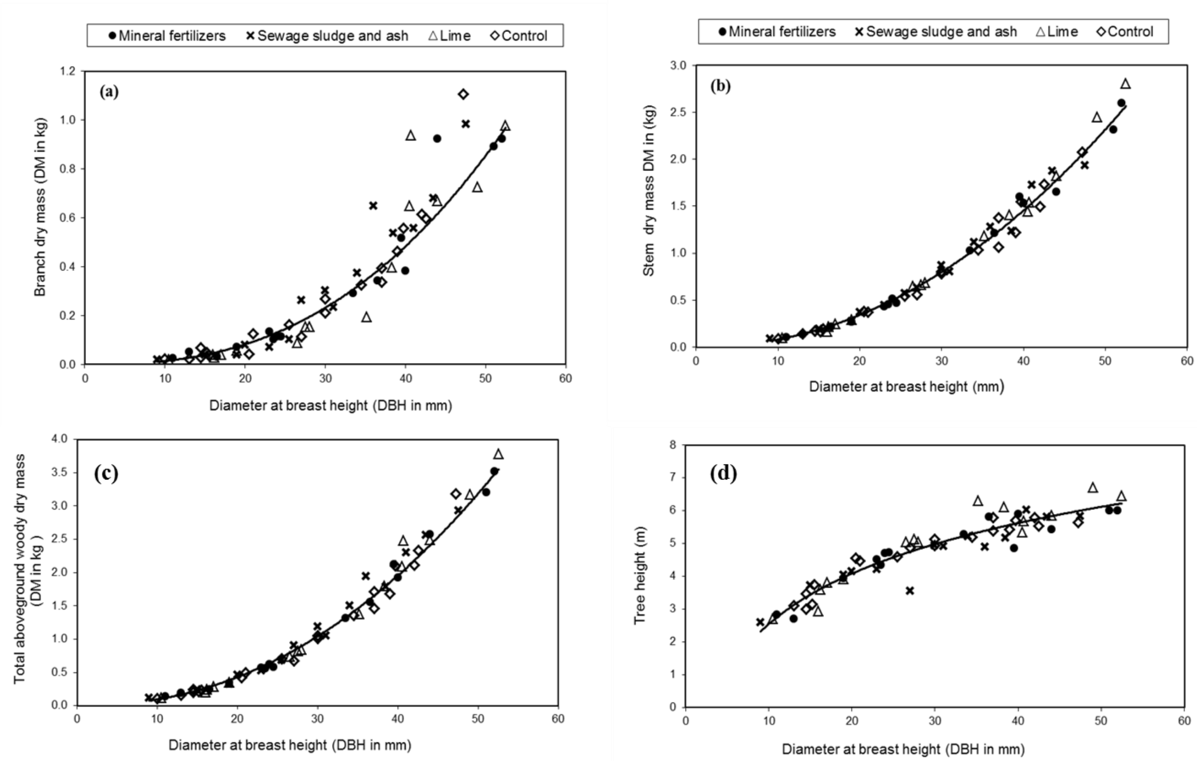

Figure 10: Power allometric relationship between stem diameter (mm) at breast height (DBH) and (a) branch dry mass (DM in kg), (b) stem dry DM in kg), (c) standing total aboveground woody dry mass (AGWDM in kg tree-1) and (d) tree height (m) in different fertilizers including control (SRWC1) in coppice after two years of plant growth (two years old coppice plantation).

To make a common and more robust allometric equation for SRC poplar clone J-105 this experiment was repeated in SRWC2 planation after two years of plant growth in coppice (two years old coppice). This plantation was not fertlized (see details in Chapter 4 section 4.1.1). For allocation of woody dry mass, allometric equations were developed for the branch, stem and total standing AGWDM (branch+stem), respectively. The values of the coefficients (R^2) are presented in **Table 7** and the regression lines are presented in **Figure 11**. R^2 values were not significantly different for both plantations (SRWC1 and SRWC2).

Table 7: Allometric power functions to etimate dry mass in branch, stem and branch+stem (total aboveground woody dry mass) poplar clone J-105 after two years of plant growth in coppice (SRWC2).

Dry mass (DM in kg)	n	Equation	R^2
Branch	25	$y = 3.00E\text{-}04x^{2.01}$	0.94

Stem	25	$y = 5.00E\text{-}04x^{2.12}$	0.98
Total aboveground	25	$y = 9.00E\text{-}04x^{2.06}$	0.97
Height (m)	25	$y = 6.62E\text{-}01x^{0.56}$	0.87

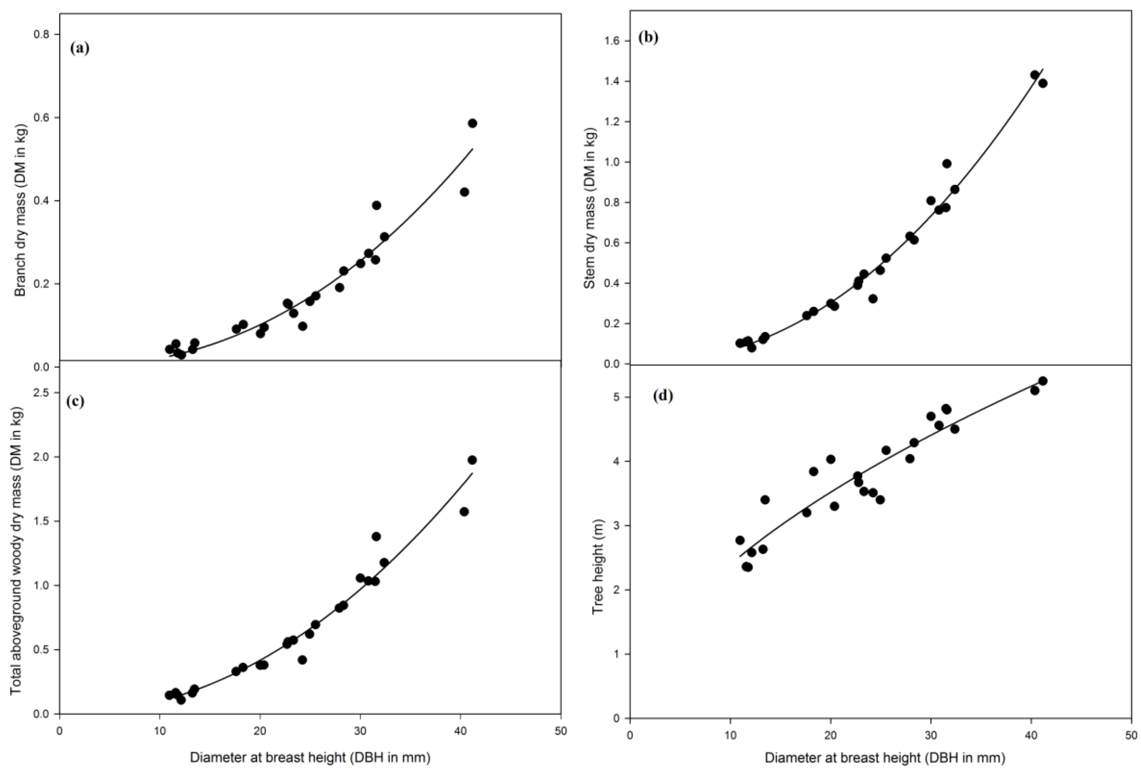

Figure 11: Power allometric relationship between stem diameter (mm) at breast hieght (DBH) and (a) branch dry mass (DM in kg), (b) stem DM (kg), (c) standing total aboveground woody dry mass (AGWDM in kg tree^{-1}) and (d) tree hieght (m) in unfertilized (SRWC2) in coppice after two years of plant growth (two years old coppice plantation).

For allocation of woody dry mass in poplar clone J-105 under SRC management equations from **Table 6** for fertilizer treatments (SRWC1 plantation) and **Table 7** for unfertilized (SRWC2 plantation) were used. In the present study results were similar to previous studies done on willows SRC (Abrahamson et al. 2002; Felix et al. 2008) and on poplar deltoids, where allometric biomass equations were distinct for above ground components (viz, bole, branch, leaf, twig, total above ground) with R^2 values ranging from 0.84 to 0.98 (Negi and Tondon 1997). In poplar, woody dry mass estimations is dependent on DBH due to the large size of the main stem (Zalesny et al. 2007; Felix et al. 2008). Bott (2014) developed allometric equations DBH vs. aboveground woody dry mass for first rotation (seven plus years old) and also for the second rotation (two years old) poplar stand in Alaska. In his study he considered two levels of DBH (30 cm and 1.3 m above the ground) for first and second rotations, respectively, where the authors found R^2 to be ranging from 0.84 to 0.87 i.e. in close agreement to the R^2 values obtained in current study. DBH alone was a very good estimator of dry mass (all R^2 values varying between 0.97 and 0.99) while R^2 values for height varied between 0.87 to 0.90, accordingly height prediction of woody dry mass was not included in thesis (**shown in Table 6 & 7).** Furthermore, the total height of the standing trees can not be measured accuratly, once they have achieved a height of more than 15 m. However, the DBH valuse can be accuratly measured for standing trees of any age group. Singh and Mishra (1995) have reported that there are no significant differences in the stadning woody dry mass in field estmated with D^2H (where D is diameter at breast height and H is total tree height). Felix et al. (2008) have observed DBH to be the best allometric estimator of woody dry mass mainly for poplar trees with diameter greater than 4 cm.

In both plantations (SRWC1 and SRWC2) in this study, there was no significant differences in R^2 values, due to overfertilization during long term argriculatural practice or it may have had no impact of fertilzation after a certain period, which indicates that the present allometric equations can be considered as a site specific for particular poplar clone J-105 on arable land to predict the standing allocation and aboveground woody dry mass. Allometric equation is a good estimator for estimation of the standing woody dry mass in forest and SRC plantations as well. Similar study was done by Chaturvedi et al. (2011) in standing trees of *Populus deltoides* in India where they found R^2 to be more than 0.95, and stated that the relationship is strong to predict the aboveground woody dry mass in standing poplar trees. The present study is also in good agreement with the results of Tahvanainen (1996) and Verwijst and Telenius (1999), where they developed a strong allometric relationship between DBH vs. aboveground woody dry mass in willows at 30 cm above the ground level for the first rotation. Numerous other studies have supported fitting of allometric function for biomass DBH curves not only for poplar but also for various other tree species (Albaugh et al. 1998; King et al. 1999; Sigurdsson et al. 2001; Delphis and Levia 2008; Komiyama et al. 2008; Basuki et al. 2009), where they have found high R^2 values ranging from 0.95 to 0.99, smilar to the present results in the thesis. This study was confind to develop allometric equations for the allocation (branch, stem and branch+stem) of above ground woody dry mass in overfertlized and non fertlized former arable land where allometric equations can be a good precitor of biomass, especailly for fast growing trees poplar clone J-105 under SRC management. However, the above presented results in this study is for the stadning allocation and estimation of aboveground woody dry mass in poplar clone J-105 only.

5.1.2. Allometric relationships for the belowground woody dry mass

After succesfully developing the allometric equations for the estimation and allocation of standing aboveground (branch+stem) woody dry mass in poplar clone J-105, the study required the estimation of standing belowground woody dry mass because of considerable amount of carbon present in the tree root system (Brunner et al. 2013; Berhongaray et al. 2013). In the current study, SRWC2 plantation (see details chapter 4 section 4.1.1) was selected to develop an allometric equation. Allometric equation was used to scale-up belowground woody dry mass components based on basal area (BA). The relationship between BA of tree stump and dry weight for the Cr (Ø >5 mm) were ploted in **Figure 12**. The allometric equation in **Figure 12** illustrates a relationship between BA (cm^2 $stump^{-1}$) and dry weight of BGWDM (kg $stump^{-1}$), a strong correlation was found where R^2 value was 0.92 (R^2~1) in power fitting line while moderate corrleation was obsrved in linear fitting line where R^2 value was 0.69 (more than 0.5). This may explain the exponential growth better than linear growth in the plantation.

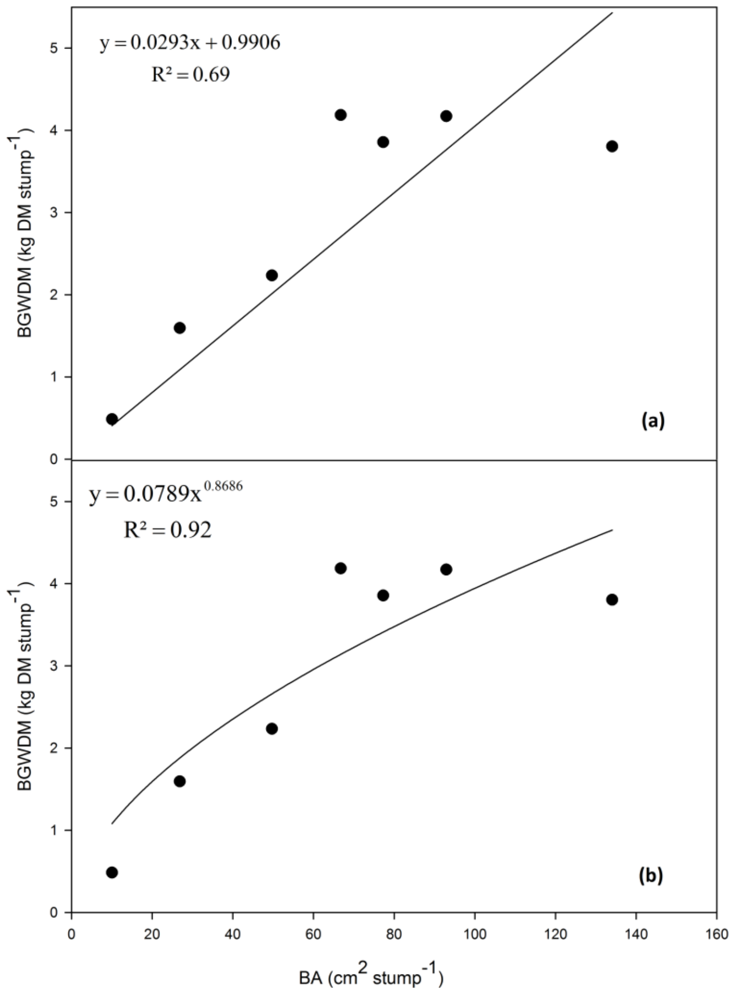

Figure 12: Comparison of (a) linear and (b) exponential relationship between belowground coarse root (Ø >5 mm) woody dry mass and basal area (BA) stump^{-1} (cm^2). An area occupied by a single tree (Voronoï polygon) in relation to its stem diameter (at 22 cm in SRWC2).

This result is in agreement with Berhongaray et al. (2014) where they have reported that R^2 ranging from 0.85-0.93 in first (uncoppiced) and second (coppiced) rotation of many poplar genotypes under SRC management on former arable lands in Flanders Belgium. This result is also supported by Chaturvedi et al. (2011), where they concentrated on development of statistical models for prediction of belowground biomass of standing trees of *Populus deltoides* from age one to nine years where they found R^2 = 0.97 i.e. close to present study results. Tondon et al. (1991) have developed allometric functions for *Populus deltoides* for total belowground biomass in Tarai region of Uttrakhand state in India with R^2 values range from 0.83 to 0.98. Singh and Mishra (1995) fitted the allometric eqautions of *Populus deltoides* for BGWDM for the state of Uttar Pradesh, India with R^2 values ranged from 0.46 to 0.96. Several other studies have supported fitting of allometric function for standing BGWDM DBH/basal area/branch+stem dry weight curves not only for poplar but also for various other tree species (Albaugh et al. 1998; King et al. 1998; Peichl and Arain 2007; McIvor et al. 2009), where high R^2 values range between 0.95 to 0.99 i.e. smilar to the results of present study. This part of study was confind to develop allometric equation for the BGWDM on former arable land where allometric equation can be a good estimator of BGWDM, especailly for poplar fast growing trees under SRC management.

5.2. Assessment of aboveground woody dry mass production in SRWC1

5.2.1. Effects of fertilizers on stool survival rate

The stool survival rate decreased across the period of the four years (from 2011-2014) and differed among the treatments in each year (**Table 8**). Maximum survival rates were observed at 82%, 77%, 80% and 60% in lime over three to six years (from 2011-2014) of plant growth in coppiced. Minimum survival rates were observed at 37%, 27%, 26% and 15 % in sludge & ash over three to six years (from 2011-2014) of plant growth in coppiced.

Dynamics of stool survival rates were observed for each year (2011-2014) with corresponding treatments (**Figure 13**). The survival rate of poplar clone J-105 among the fertilizer treatments including control, were significantly different on 95 % confidence (where $p<0.05$) level in control vs. sludge & ash, lime vs. mineral, lime vs. sludge & ash.

Annual survival rates decreased within the treatments among the year (from 2011-2014) but this change was not significant.

Table 8: Annual average survival rate (%) of stool, standard deviation (SD±), standard error (SE) and confidence interval (CI) in fertilizers (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014) for poplar clone J-105 in coppice rotation.

Treatments	Year	Annual survival rate (%)	SD (±)	SE	CI
Control	2011	68	16	9	40
Lime	2011	82	25	15	63
Mineral	2011	47	37	21	92
Sludge & Ash	2011	37	15	8	36
Control	2012	62	21	12	53
Lime	2012	77	21	12	53
Mineral	2012	42	35	20	87
Sludge & Ash	2012	27	15	8	37
Control	2013	56	22	13	54
Lime	2013	80	23	13	57
Mineral	2013	43	41	24	101
Sludge & Ash	2013	26	14	8	36
Control	2014	54	13	7	31
Lime	2014	60	13	7	31
Mineral	2014	37	35	20	87
Sludge & Ash	2014	16	14	8	35

Such a trend was seen due to reasonable interactions between individual stools leading to high mortality rate in small stools. In literature, significant percentage variations were noted for the stool survival rates, which decreased with increase in the number of rotation cycles for willow (Verwijst 1996; Labrecque & Teodorescu 2005) and for poplar (Afas et al. 2008). In the case of lime, survival rate slightly increased from 2012-2013 while in case of control, mineral and sludge & ash slightly decreased or may have remained constant because of not much change in precipitation and temperature in the both growing seasons in 2012 and 2013. Laureysens et al. (2005) have reported in many of their growth studies, that use of fertilizer does not affect the growth rates of poplar. The lowest survival rates in the current study were for sludge & ash, possibly because of the poor rooting capacity (Dickmann and Stuart 1983). The survival rates decreased very fast after five and six years of plant growth which might be because of high competition with weeds or showing partial interest in long-term plantations (Afas et al. 2008). Stump survival rates could have been affected by plant density, as of competition for light between single stumps (Verwijst & Nordh 1992). Kopp et al. (1996) reported that survival rates could be depending on rotation length and it can be decreased in longer rotation than shorter rotations.

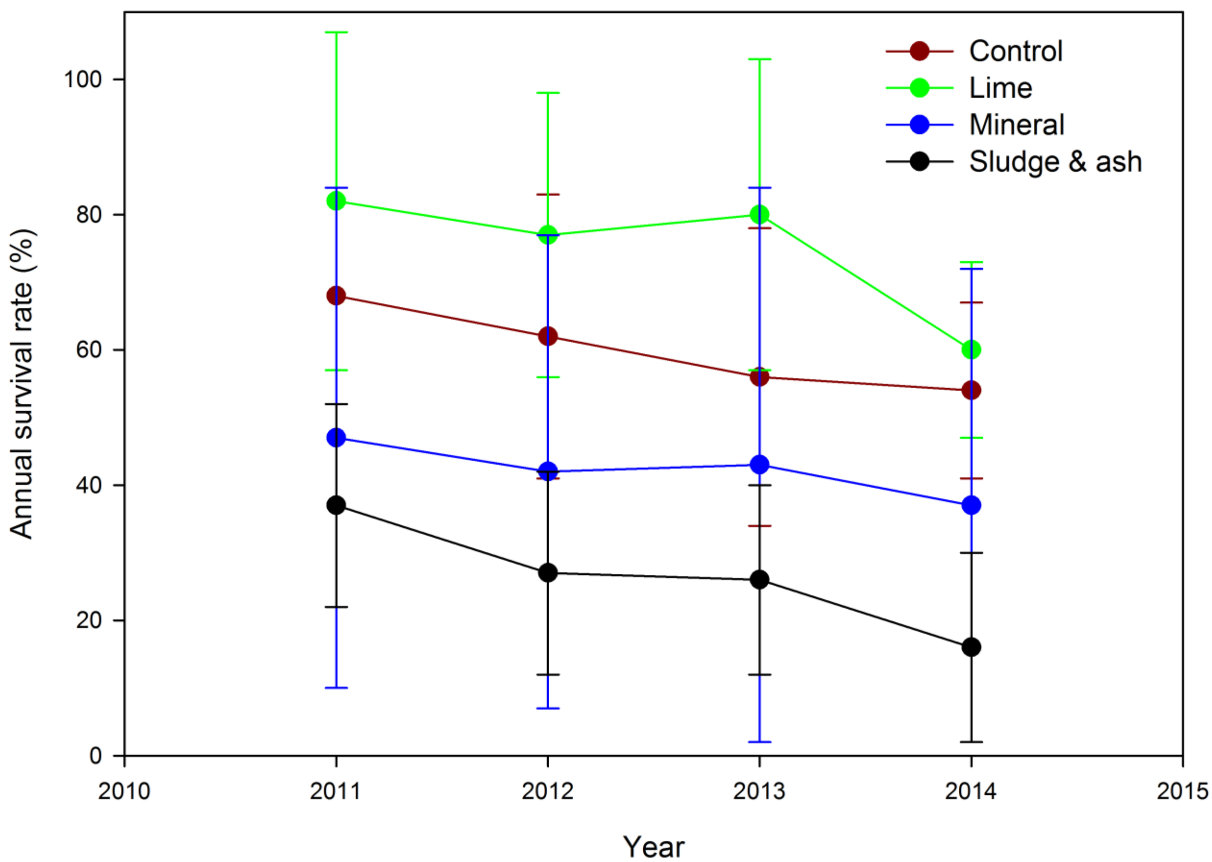

Figure 13: Time course of survival rate (%) in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014). Mean values of replicates for each fertilizer treatments including control and vertical bars show standard deviation (SD±) for poplar clone J-105 in coppice.

5.2.2. Effects of fertilizers on number of shoots per stool

In all fertilizer treatments and control, sprouting was fast after coppicing. However, the number of shoots differed among the treatments every year but those are not significantly different at 95 % confidence level (Tukey test, $p>0.05$) among the treatments in the same year (**Figure 14**). Maximum number of shoots per stool was 5.2 observed in lime after four years (2013) while lowest number of shoots per stool was 3.6 in control of plant growth in coppice (**Table 9**).

Table 9: Annual average number of shoots per stool (no.) of stool, standard deviation (SD±), standard error (SE) and confidence interval (CI) in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014) for poplar clone J-105 in coppice.

Treatments	Year	Annual shoots stool^{-1} (no)	SD (±)	SE	CI
Control	2011	4.5	0.7	0.4	1.8
Lime	2011	4.2	1.0	0.6	2.6
Mineral	2011	4.2	0.6	0.4	1.6
Sludge & Ash	2011	4.2	0.2	0.1	0.5
Control	2012	4.3	0.5	0.3	1.2
Lime	2012	4.6	0.7	0.4	1.7
Mineral	2012	3.9	0.6	0.4	1.6
Sludge & Ash	2012	4.0	0.4	0.2	0.9
Control	2013	4.9	0.9	0.5	2.3
Lime	2013	5.2	0.5	0.3	1.2
Mineral	2013	4.0	0.8	0.5	2.1
Sludge & Ash	2013	4.5	0.2	0.1	0.5
Control	2014	3.4	0.4	0.3	1.1
Lime	2014	3.6	0.2	0.1	0.5
Mineral	2014	3.4	0.1	0.1	0.3
Sludge & Ash	2014	3.9	0.0	0.0	0.1

Number of shoots per stool decreased with increase in time (age of the trees, **Figure 14**); however, in some cases it increased (for example after five years). Such a course was observed because of weather effect or rainfall. Number of shoots varied, three to five per stools among the treatments and years (**Figure 14**). These results are in coherence with a poplar study done by Ceulemans et al. (1996), where they have reported five to eight shoots per stool. The early number of sprouts in subsequent harvest upsurges with consecutive rotations, because the number of bud depends on the number of enduring stem parts on the harvested stool (Sennerby-Forsse et al. 1992). During the first rotation coppice plantation, number of shoots per stool among years decreased (Liberloo et al. 2005), in the current study shoots per stool is decreasing across the years in all treatments including control. Pontailler et al. (1999) had observed poplar over five two-year rotations where number of shoots increased with increase in the number of rotations but it decreased within rotations. After the first coppicing, Laureysens et al. (2003), observed on an average three to seven shoots per stool among the different poplar clones in Boom near Antwerp on waste disposal sites which is similar to current study in Domanínek, Czech Republic among the different fertilizer treatments in different year after first coppicing.

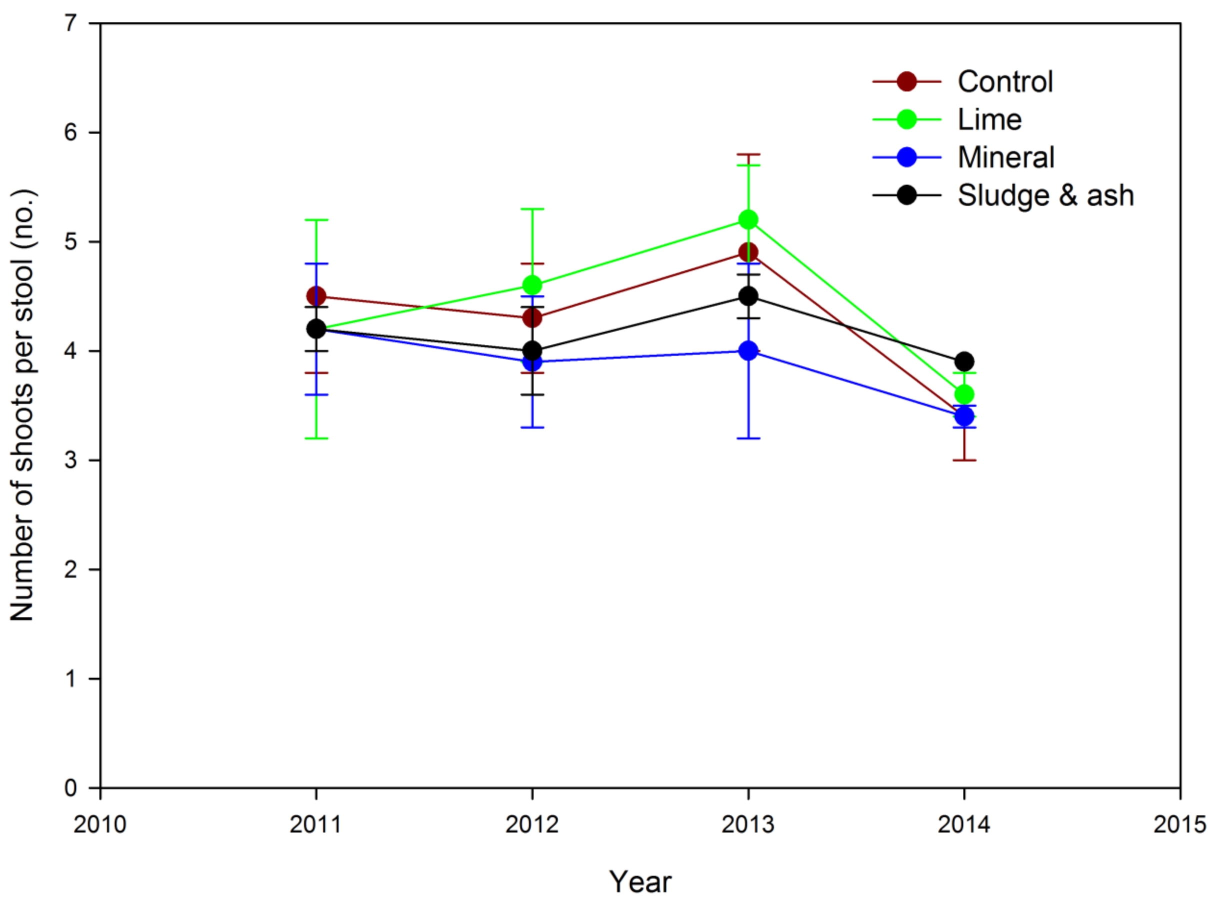

Figure 14: Time course of shoots per stool (number) in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014). Mean values of replicates for each fertilizer treatments including control and vertical bars show standard deviation (SD±) for poplar clone J-105 in coppice.

5.2.3. Effects of fertilizers on annual aboveground woody dry mass

In the present study, the hypothesis (null hypothesis) was stated as, after the first harvest (uncoppiced) on former arable land, the application of fertilizers will have no effect on the AGWDM (**Figure 15**).

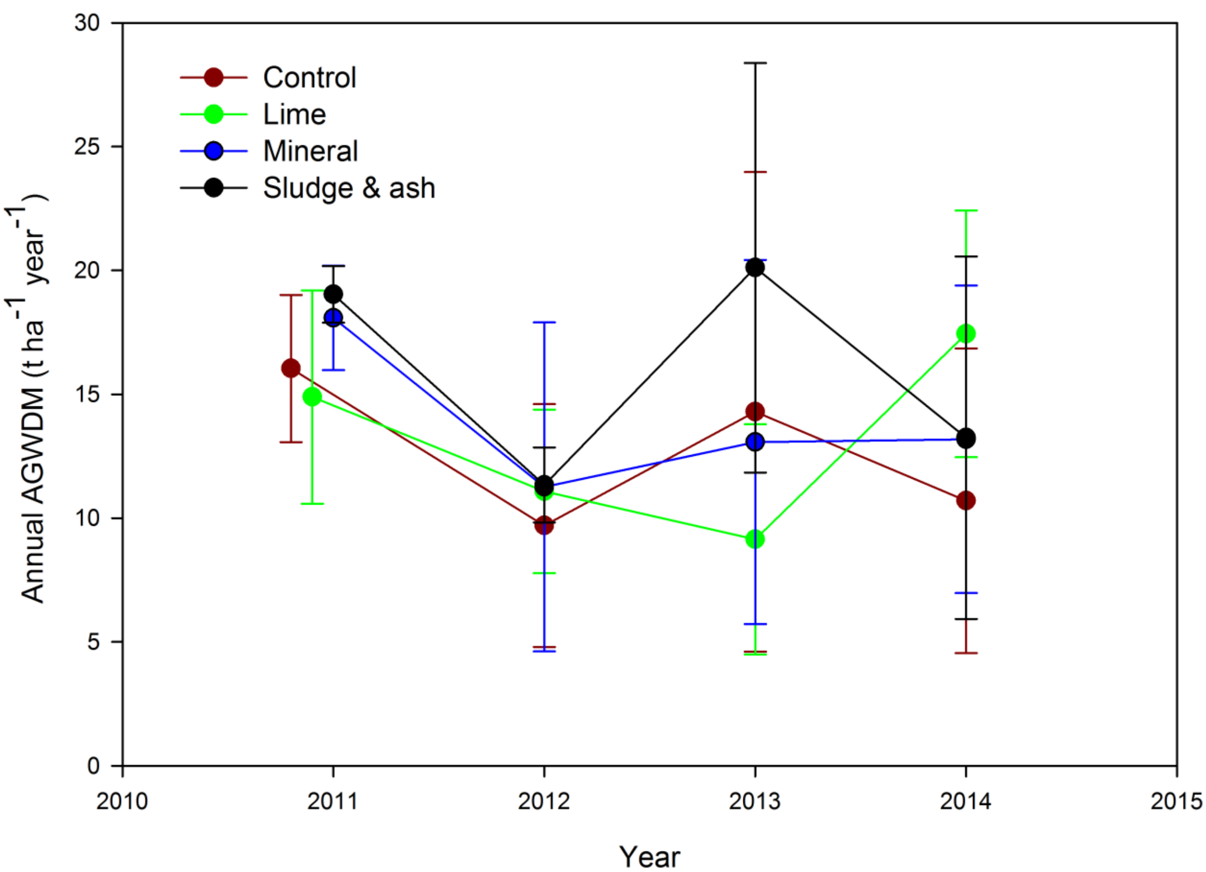

Figure 15: Time course of annual aboveground woody dry mass (AGWDM, t ha^{-1} year^{-1}) in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014). Mean values of replicates for each fertilizer treatments including control and vertical bars show standard deviation (SD±) for poplar clone J-105 in coppice.

Average AGWDM varies between 9.14±4.65 to 20.11±8.27 t ha^{-1} year^{-1} (**Table 10**), the poplars in coppice rotation were unaffected by fertilizer application for all parameters like survival rates, number of shoots per stool and dry weight did not vary between the fertilized (mineral, lime and sludge & ash) and unfertilized (control) plots, and there was no significant ($P>0.05$) difference between the annual AGWDM among the treatments within the years 2011-2014 (**Figure 15**). Thus, based on these results null hypothesis could not be rejected. The fertilizers did not have any impact on standing annual AGWDM production, due to root systems being already developed in first rotation (uncoppiced) and land being over fertilized during growing of the long term agricultural crops as a result there was no impact of fertilizers on second rotation (coppiced). In 2011, annual biomass was higher than that of 2012, 2013 and 2014 due to fast growth and sprouting of coppice at the beginning of one to three years, while in 2013 sludge & ash yielded more annual woody dry mass as compared to previous years and also in comparison to other treatments in the same year, due to climatic factors and additional number of shoots sprouting. However, this was not significantly different. Guillemette and DesRochers (2008) reported direct application of a slow release of fertilizer to the base of the tree stem upon planting for best fertilization results, ensuring more nutrient uptake by the targeted trees, rather than weeds.

In a study (fast growing hybrid poplar, DesRochers et al. 2006) authors have reported the effects of fertilizer application to be relatively small in second and third growing season of poplar sp. and also negative effects of nitrogen fertilization on growth of some poplar clones such as 33 and 794. Results of current study is similar to previous studies, however sludge & ash, and lime has more growth with increase in the number of growing seasons, due to environmental factors which are however not significantly different among the fertilizer treatments including control in the same year. Heilman et al. (1999) reported nutrients leached from soils are almost negligible in SRF in temperate area or under natural forest conditions. Schwabisch (1994) suggested maintenance of nutrients (N, P, K and Ca) by the frequent use of mineral or organic fertilizers in agricultural soils.

According to DesRochers et al. (2006) and Van den Driessche (2007) mineral fertilizers (mainly N) may restrict the growth of stems, reduce the height and basal area. However, P and K fertilization have no effect on growth, during the first year of planting. Dry mass production of hybrid poplar stands, between 5 and 10 years old range from 12.03 to 38.50 t ha^{-1} $year^{-1}$ (Dickmann and Stewart 1983) and values of 38.99 t ha^{-1} $year^{-1}$ have been reported for 6-years old *populus deltoides* (Blackmon and white 1972). Current results of woody dry mass are similar to the previous studies that did not show impact of fertilizers on biomass production. AGWDM of hybrid poplars was higher in organic fertilizers than the inorganic and control treatments (Lteif et al. 2007) which are similar to lime and sludge & ash results after five-six years growth in the current study.

In divergence, Adegbidi et al. (2001) and Coleman et al. (2004) reported that fertilizers can be more effective or have positive impact on biomass production of poplars in the dose of 224–336 kg N ha^{-1} year^{-1} and 50 kg N ha^{-1} year^{-1}. The fertilizers did not influence the biomass production because a high amount of fertilizer could be leached and the fertilizer demand of the trees would be covered by deposition and mineralization.

Table 10: Average annual aboveground woody dry mass (AGWDM, t ha^{-1} year^{-1}) standard deviation (SD±) standard error (SE) and confidence interval (CI) in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014) for poplar clone J-105 in coppice.

Treatments	Year	Annual AGWDM (t ha^{-1} year^{-1})	SD (±)	SE	CI
Lime	2011	14.89	4.31	2.49	10.71
Mineral	2011	18.08	2.11	1.22	5.23
Sludge & Ash	2011	19.03	1.14	0.66	2.82
Control	2012	9.7	4.9	2.83	12.18
Lime	2012	11.08	3.3	1.9	8.19
Mineral	2012	11.26	6.64	3.83	16.49
Sludge & Ash	2012	11.34	1.51	0.87	3.75
Control	2013	14.29	9.68	5.59	24.04
Lime	2013	9.14	4.65	2.68	11.55
Mineral	2013	13.07	7.35	4.24	18.26
Sludge & Ash	2013	20.11	8.27	4.77	20.54
Control	2014	10.7	6.15	3.55	15.29
Lime	2014	17.44	4.98	2.88	12.38
Mineral	2014	13.18	6.21	3.58	15.42
Sludge & Ash	2014	13.25	7.32	4.22	18.18

5.2.4. Effects of fertilizers on cumulative aboveground woody dry mass

Current study did not show significant differences in mean annual woody dry mass among the treatments within the year. The null hypothesis was cross checked to find the differences between total or cumulative aboveground woody dry mass among the treatments within the year and among the year within the treatments (**Figure 16**). Cumulative AGWDM was significantly different ($p>0.001$ and 0.01, respectively) when number of growing seasons or age of trees increased (**Figure 16**) it varied from 31.02±7.13 to 83.15±8.88 t ha^{-1}. Minimum cumulative woody dry mass was found in lime after three years of plant growth and maximum was in sludge & ash after six years of plant growth in coppice (**Table 11**).

Table 11: Average cumulative aboveground woody dry mass (AGWDM, t ha^{-1}) standard deviation (SD±) standard error (SE) and confidence interval (CI) in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) over four years (2011-2014) for poplar clone J-105 in coppice.

Treatments	Year	Cumulative AGWDM (t ha^{-1})	SD (±)	SE	CI
Control	2011	31.45	3.17	1.83	7.88
Lime	2011	31.02	7.13	4.11	17.70
Mineral	2011	38.04	1.10	0.64	2.74
Sludge & Ash	2011	38.45	4.18	2.41	10.39
Control	2012	41.15	7.32	4.23	18.18
Lime	2012	42.10	10.00	5.78	24.85
Mineral	2012	49.30	7.19	4.15	17.85
Sludge & Ash	2012	49.80	4.92	2.84	12.21
Control	2013	55.44	8.46	4.89	21.02
Lime	2013	51.25	14.25	8.23	35.40
Mineral	2013	62.37	14.35	8.28	35.65
Sludge & Ash	2013	69.90	11.90	6.87	29.56
Control	2014	66.14	8.32	4.80	20.67
Lime	2014	68.68	18.39	10.62	45.69
Mineral	2014	75.55	20.47	11.82	50.85
Sludge & Ash	2014	83.15	8.88	5.13	22.07

However, production of aboveground cumulative woody dry mass did not significantly differ among the treatments within the particular year (2011-2014) such as from 3rd to 6th years of growth. Thus, the results did not reject the null hypothesis. While the fertilizers did not have impact on mean annual and cumulative AGWDM production because root systems were already developed in first rotation (uncoppiced) and land was over fertilized during growing of the long term agricultural crops so that there were no impact of fertilizers on second rotation (coppiced). In 2011 (3rd year of plant growth in coppice) cumulative AGWDM was lesser than the 2012 (4th year of plant growth in coppice), 2013 (5th year of plant growth in coppice) and 2014 (6th year of plant growth in coppice) because height and DBH of trees increased with increase in the age of trees. Cumulative AGWDM from 26 to 83 t ha^{-1} after four to five years of plant growth in coppice at different sites and in different poplar clones (Dowel et al. 2009; Paris et al. 2011) while plant density was 10,000 plants ha^{-1} while in current study, tree's density was 9216 plants ha^{-1} (~10000), however, maximum yield (**see Table 11**) was reported after six years of plant growth but current results are similar to the previous studies (Lauresyens et al. 2003, 2004).

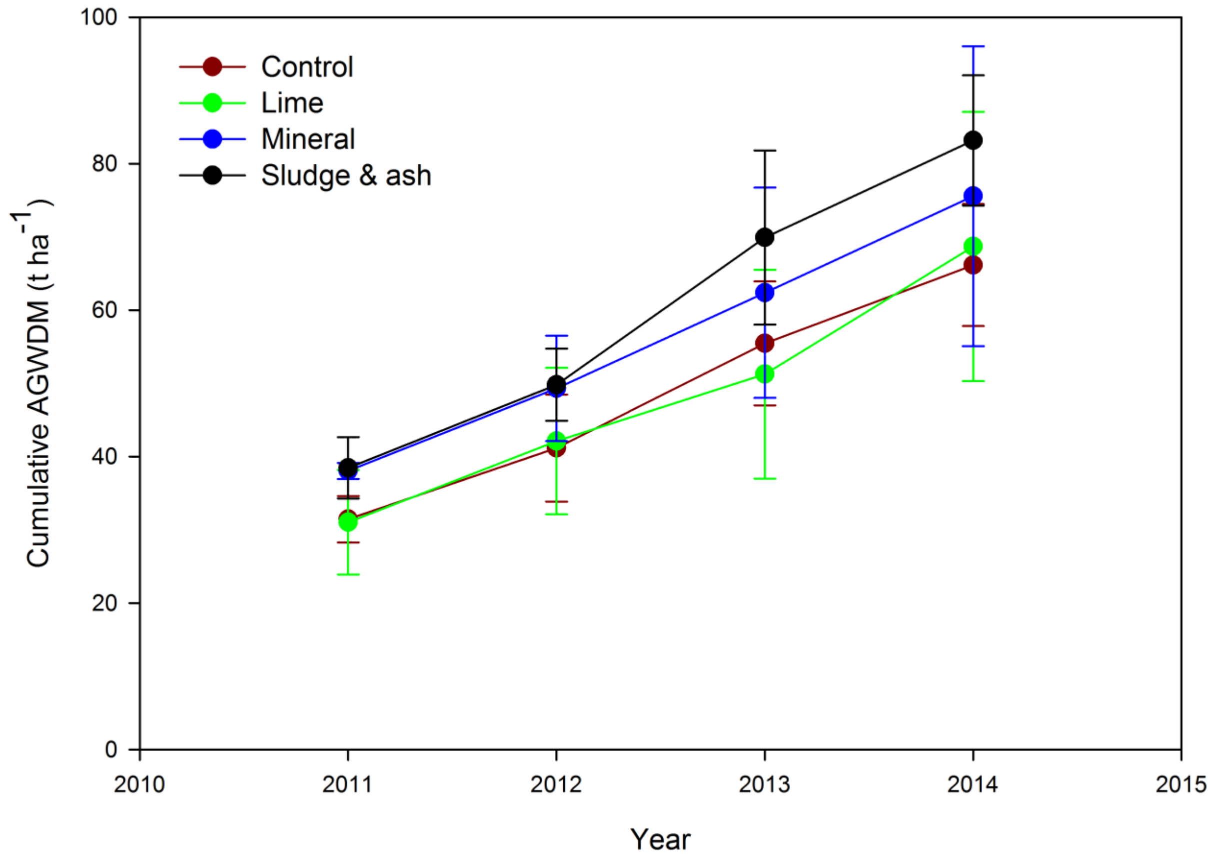

Figure 16: Time course of cumulative aboveground woody dry mass (AGWDM, t ha^{-1}) for poplar clone J-105 in fertilizer treatments (mineral, lime, sludge & ash) and unfertilized (control) under short rotation coppice (second rotation/coppiced established in winter 2008/2009) over four years (2011-2014) study where plants growth three to six years. Mean values of replicates and standard deviations (SD±) are shown by vertical bars.

5.3. Assessment of aboveground woody dry mass production in SRWC2

5.3.1. Dynamics of stools

The stool survival rate decreased over the five years in coppice (second rotation). It varies from 80 to 70% from the 2 to 5 years of plant growth (**Table 12**). Maximum survival rate was observed to be 80% in 2011 (after two years plant growth in coppice, first year data missing) and minimum survival rate was 70% in 2014 (after five years of plant growth).

Table 12: Average annual stool survival rate (%), standard deviation (SD±), standard error (SE) and confidence interval (CI) in over four years (2011-2014) and over five growing seasons from GS2-GS5 for poplar clone J-105 in coppice.

Year	Growing season (GS)	Survival rate (%)	SD (±)	SE	CI
2011	GS2	79.58	6.09	2.48	6.39
2012	GS3	77.48	4.95	2.02	5.19
2013	GS4	73.56	6.60	2.69	6.92
2014	GS5	70.36	9.09	3.71	9.54

This implied that with increase in number of years, percentage of stools survival rate decreased. Stools survival rates were not significantly different (p>0.05, see **Figure 17**). Verwijst (1996) reported stool survival rate varied significantly among the parentages and increasing the number of rotations for willow. There was an expeditious decrease in stools survival rate after 5 to 6 years of plants growth because of high competition with weeds or showing partial interest in longstanding plantations (Afas et al. 2008). Current study is similar to the previous studies where stump survival rates could have been affected by plant density, as of competition for light between single stumps (Willebrand & Verwijst 1993). Kopp et al. (1997) reported survival rates could be depending on rotation length and it can decrease in longer rotation than shorter rotations. Nordh and Verwijst (2004) stated that survival rate varied from 50% to 100% in different willow clones after 4 years of plant growth which is similar to current studies for poplar in first coppice rotation.

Conversely, they were lower than 92–99% in poplars as reported by Ceulemans et al. (1996) or those found by Havlíčková et al. (2005). The survival rates may vary not only among individual clones but also vary among their replicates and years, which may explain a significant portion of mean annual increment (MAI) intraspecific variability (Trnka et al. 2008). For intraspecific variability of biomass, the survival rates are highly prejudiced by the competition with weeds during the plantation establishment. Kauter et al. (2003) have reasoned that some of the perennial weeds (e.g. *Cirsium arvense*) can have up to 80% mortality rates if the plots are untreated. Nordh &Verwijst (2004) have reported survival rate for 12 willow clones under coppice rotation which was ranging from 50% to 100% while overall mean survival rate was 90% which varies in different clones and years. In a study Laureynses et al. (2003) observed that survival or mortality rate was not dependent on plant or cutting densities, but it could be depending on the environmental conditions and rust infections.

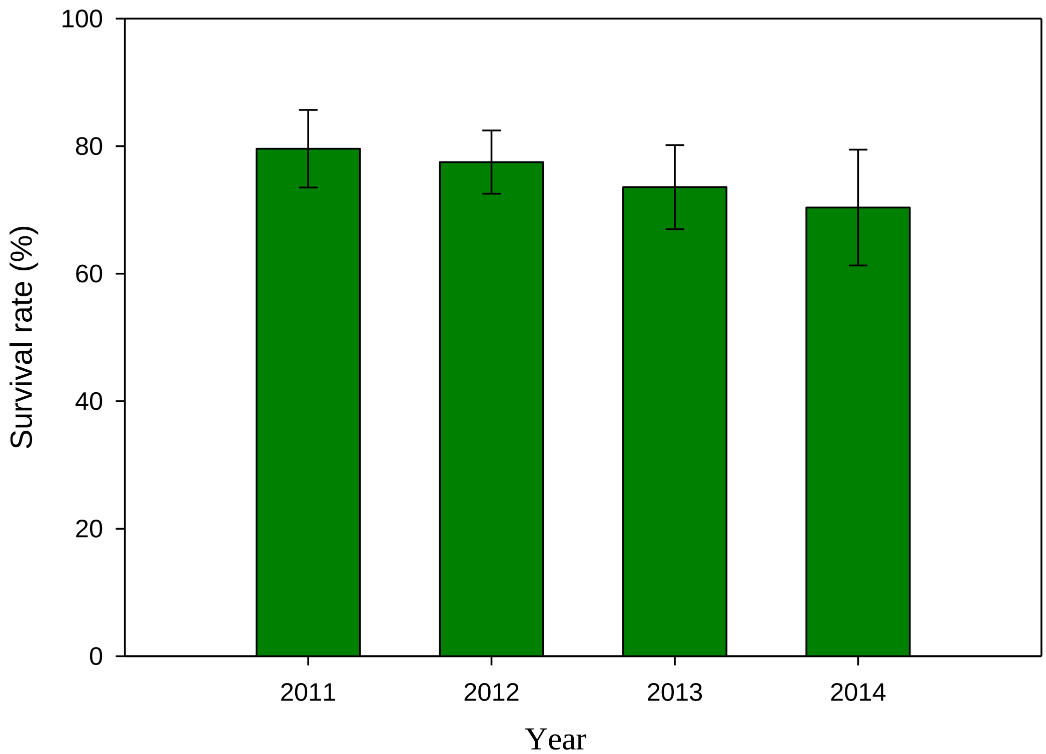

Figure 17: Time course of stool annual survival rate in percentage (%) for poplar clone J-105 in a short rotation coppice (second rotation/coppiced established in winter 2009/2010) culture over four years (2011-2014, plants growth two to five years). Mean values of replicates and standard deviations (SD±) are shown by vertical bars.

Laureynses et al. (2003) found less survival rate (58%) in poplar coppice which was heavily infected by *Melampsora larici-populeum*. Besides, stool survival rates could have been affected by plant density, because of competition for light between individual shoots (Ford & Diggle 1981; Cannell et al. 1988; Verwijst 1993; Labrecque & Teodorescu 2005), and by rotation interval, with longer rotations having marginally higher mortality than shorter rotations (Kopp et al. 1997). However, current study is similar to previous studies where dynamics of stool survival rate of poplar under coppice rotation management is decreasing when number of years and plant growth competition is increasing.

5.3.2. Dynamics of shoots

Poplar clone sprouted vigorously after the coppicing. In current study, at the beginning of the second year after coppice (2011), measurements for the evaluation of number of shoots per stumps were commenced. Prior to this evaluation, normality test (Shapiro test) was performed to determine normal distribution of shoots per stumps. Mean number of shoots per stumps varied from 4.49 to 7.08 in different growing seasons (GS2-GS5) from 2011 (plant growth two years after the coppice) to 2014 (plant growth five years after the coppice, **Table 13**). However patterns of number of shoots decreased in order from 2011 to 2013 (plants growth from two to four years growth after coppice) while it suddenly increased in 2014 (plants growth five year after the coppice, **Figure 18**), however, this variation (from 2013-2014) was non-significant ($p>0.05$, Tukey test) while variation of shoots per stump significantly ($p<0.05$, Tueky test) differed in few growing seasons which are shown in **Figure 18**. It could be related to environmental (less rainfall and high temperature) factors. In coppicing, an increase in the number of shoots per stool has been observed with the increase in the number of rotations, perhaps due to an increase in the potency or well-establishment of the rooting system with time (Verwijst 1993; Ceulemans et al. 1996; Afas et al. 2008). Conversely, within each rotation, the number of shoots per stool decreased from year to year. It is in line with previous observations of poplar clones over three to five rotations by Pontailler et al. (1999) & Afas et al. (2008) and within one rotation by Liberloo et al. (2005) & Dillen et al. (2011). Current study is similar to earlier studies, however, during the first rotation, the decreasing number of shoots per stool among years was less important as compared with the 2^{nd} and 3^{rd} rotations (Pontailler et al. 1999). In a study Afas et al. (2008) have observed, the *P. nigra* parentage exhibited the largest number of living shoots per stool over the three rotations (11 years) while another multi-rotation study was reported by Pontailler et al. (1999), where they found the *P. trichocarpa x P. deltoides* genotype exhibited the highest number of shoots per stool over five two-year rotations, while the *P. deltoides x P. nigra* genotype produced the highest number in the third and fourth rotations. Auclair & Bouvarel (1992), Ceulemans et al. (1996), Hofmann-Schielle et al. (1999), Laureysens et al. (2003, 2004) Afas et al. (2008) have reported, the genotypes with a low number of shoots denoted robust competition leading to one or two dominant shoots (*P. trichocarpa x P. deltoides* and *P. trichocarpa* genotypes) on one hand. On the other hand, genotypes with a high number of shoots per stool had weak competition leading to many shoots per stool (*P. nigra* and *P. trichocarpa* x *P. balsamifera* genotypes).

Table 13: Average shoots per stump (no.), standard deviation (SD±), standard error (SE) and confidence interval (CI) in over four years (2011-2014) and five growing seasons from GS2-GS5 for poplar clone J-105 in coppice.

Year	Growing season (GS)	Shoots stumps^{-1} (no.)	SD (±)	SE	CI
2011	GS2	7.08	0.97	0.40	1.02
2012	GS3	6.20	1.00	0.41	1.05
2013	GS4	4.49	0.54	0.22	0.57
2014	GS5	5.21	1.41	0.58	1.48

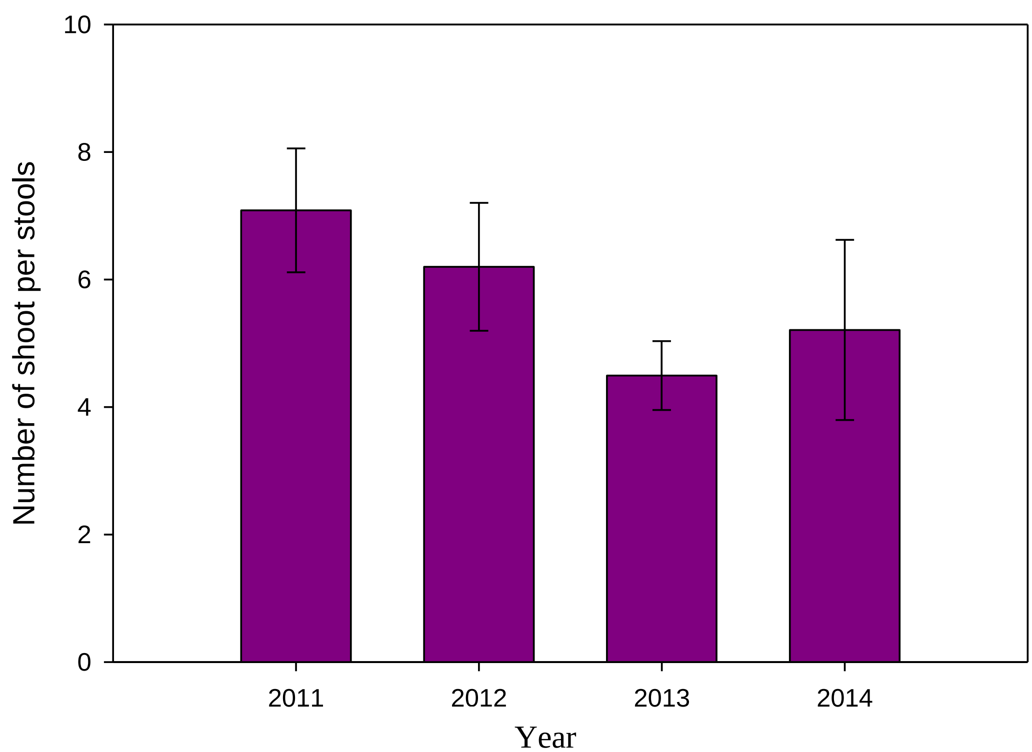

Figure 18: Dynamics of number of shoots per stool (no.) for poplar clone J-105 in a short rotation coppice (second rotation/coppiced established in winter 2009/2010) culture over four years (2011-2014, plants growth two to five years). Mean values of replicates and standard deviations (SD±) are shown by vertical bars.

5.3.3. Dynamics of aboveground woody dry mass

Average annual aboveground woody dry mass (AGWDM) increased in within coppice rotation. In the current study, not significant ($p>0.05$, Tukey test) annual increment of AGWDM was observed among the years (from 2011 to 2014) or growing seasons (GS2 to GS5) in coppice poplar clone J-105 (**Figure 19a**). Average annual AGWDM varied from 8.29 to 11.02 t ha^{-1} year^{-1}. Maximum AGWDM (11.02 t ha^{-1} year^{-1}) was observed in GS4 (2013) and minimum (8.29 t ha^{-1} year^{-1}) in GS2 (2011) **(Table 14)**. In first four growing seasons, annual AGWDM increased and in fifth growing season it decreased (**Figure 19a**). In the present study, significant ($p<0.001$, Tukey test) changes were observed in average cumulative AGWDM from 2011-2014 (**Figure 19b**) over five growing seasons (GS2 to GS5, **Table 14**). Maximum mean cumulative AGWDM (43.85 t ha^{-1} year^{-1}) was observed in GS5 (2014) and minimum mean (11.91 t ha^{-1} year^{-1}) in GS2 (2011) **(Table 14)**. Similar results were reported in previous studies where Laureysens et al. (2004) have found average annual AGWDM varying from 2.2 t ha^{-1} year^{-1} for Gibecq and 11.4 t ha^{-1} year^{-1} for Hazendans poplar clones.

Table 14: Average annual aboveground woody dry mass (AGWDM, t ha^{-1} year^{-1}), cumulative AGWDM (t ha^{-1}) standard deviation (SD±), standard error (SE) and confidence interval (CI) in over four years (2011-2014) and five growing seasons from GS2-GS5 for poplar clone J-105 in coppice.

Year	Growing Season (GS)	Annual AGWDM (t ha^{-1} year^{-1})	SD (±)	SE	CI	Cumulative AGWDM (t ha^{-1})	SD (±)	SE	CI
2011	GS2	8.29	1.48	0.6	1.55	11.91	1.48	0.6	1.55
2012	GS3	10.01	0.73	0.3	0.76	21.92	1.46	0.6	1.53
2013	GS4	11.02	0.61	0.25	0.64	32.94	1.57	0.64	1.65
2014	GS5	10.91	3.8	1.55	3.99	43.85	4.58	1.87	4.81

Other studies report annual four year rotation woody dry biomass of 1.2–13.6 t ha^{-1} for numerous poplar species, reliant on clone, soil, climate and monitoring management (Strong and Hansen 1993; Beale & Heywood 1997; Armstrong & Johns 1999). In another study average annual AGWDM of *P. trichocarpa* x *P. deltoides* (TxD) clones of 27.8– 35.2 t ha^{-1} and *P. trichocarpa* (T) clones of 16.3–27.5 t ha^{-1} was reported by Heilman & Stettler (1985), Heilman & Xie (1993) Heilman et al. (1994), and Scarascia-Mugnozza et al. (1997) in the best environmental conditions such as favorable climate, fertilization, and irrigation. Cannell & Smith (1980) have stated the annual woody biomass production of the best performers Hoogvorst (i.e. T x D clones) and Hazendans with a maximum of 14.3 and 12.8 t ha^{-1}, respectively, and T clones Columbia River, Fritzi Pauley and Trichobel with a maximum biomass between 11.4 and 13.7 t ha^{-1}, can be considered high, relating it to the non-optimal soil conditions.

According to Dickmann and Stuart (1983), poplar can grow nearly everywhere, but high performance shows on the preeminent sites (richness soil nutrient and water availability). Current results support the overall time course of woody dry mass of poplar for five years in coppice management is about the same as it was already studied at different places for different clones.

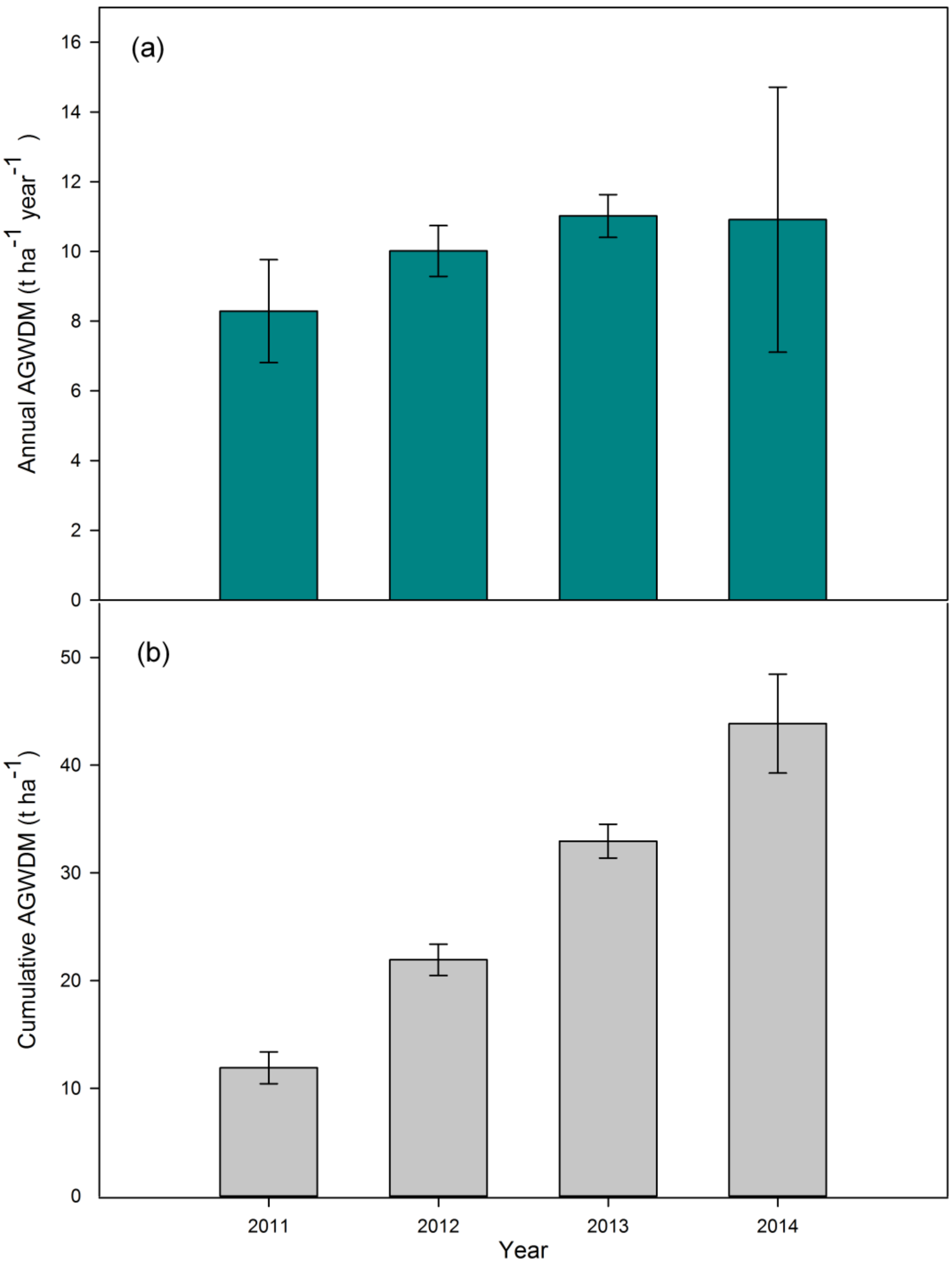

Figure 19: Time course of (a) annual aboveground woody dry mass (AGDMM, t ha^{-1} year^{-1}) and (b) cumulative AGDMM (t ha^{-1}) for poplar clone J-105 in a short rotation coppice (second rotation/coppiced established in winter 2009/2010) culture over four years (2011-2014, plants growth two to five years). Mean values of replicates and standard deviations (SD±) are shown by vertical bars.

In four year-rotation of poplar on marginal sites with low fertility biomass was reported to be 2.3–9.2 t ha^{-1} $year^{-1}$ (Bungart & Huttl 2001). In the current study standing total AGWDM was 43.85 t ha^{-1} (after five years of plant growth in coppice rotation, total age of standing root system was 13 years) while in other study it was reported to be 22.1 t ha^{-1} on municipal waste land (after six years of plant growth in uncoppiced, Felix et al. 2008). This significant difference could be because of sites, environmental conditions and clonal differences. In other studies clonal variation was reported on homogenous sites (Ceulemans et al. 1992; Heilman et al. 1994). Annual biomass of poplar clone was found to be between 2.2 to 13.6 t ha^{-1} $year^{-1}$ in Great Britain and Sweden (Vande Walle et al. 2007).

In several other studies authors have observed higher biomass production in small plot experiments with some cases reported over 18 t ha^{-1} $year^{-1}$ (Ceulemans et al. 1996; Armstrong et al. 1999; Laureysens et al. 2004; Labrecque & Teodorescu 2005). Most of the studies are done for dynamics of biomass in different rotation cycles for example, Nassi O Di Nasso et al. (2010) have reported the biomass production to have increased within the first three rotations and then decreased from the first harvest onwards while they found maximum biomass in long term rotations. In another study, Deckmyn et al. 2004 have reported strong relationship with the rotation cycle and productivity of the stand. The data reported in the literature partly confirms current study results. Conversely, it is hard to compare woody dry mass from different studies, as the methods used for crop management differ from study to study. Overall, current study can be reported as a first study in Czech Republic where, intensive and long term monitoring have been carried out for poplar clone J-105 to evaluate the plant growth under SRC management. After studying the above ground biomass at two different sites, in different ages and treatments, analysis of the dynamics of belowground biomass especially coarse roots was carried out.

5.4. Assessment of belowground woody dry mass (BGWDM)

In the current study, annual belowground woody dry mass (BGWDM) was observed among the years (2012 to 2014) over three years for five growing seasons (GS3 to GS5) in coppice (first harvest in 2009) poplar clone J-105 (**Figure 20a**). Average annual BGWDM varied from 3.02 to 2.5 t ha^{-1} year^{-1} (**Table 15**). Maximum annual BGWDM (3.02 t ha^{-1} year^{-1}) was observed in GS3 (2012) and minimum (2.5 t ha^{-1} year^{-1}) in GS5 (2014). Annual BGWDM was not significantly different (p>0.05) among the years (from 2012-2014, **Figure 20a**). Age of trees increased while annual belowground biomass decreased which may pertain to already well developed root system (total age 11 years). On other hand cumulative BGWDM was observed for four years (from 2011-2014) over five growing seasons (GS2-GS5) and average cumulative BGWDM varied between 4.71-13.22 t ha^{-1} (**Table 15**). Cumulative BGWDM was increased significantly (p>0.001) (**Figure 20b**) in all growing seasons from GS2 to GS5 (2011 to 2014).

Table 15: Average annual belowground woody dry mass (BGWDM, t ha^{-1} year^{-1}) for growing season GS3 to GS5 (2012-2014) and cumulative BGWDM (t ha^{-1}) for growing season GS2-GS5 (2011-2014), standard deviation (SD±), standard error (SE) and confidence interval (CI) in coppice poplar clone J-105.

Year	Growing Season (GS)	Annual BGWDM (t ha^{-1} year^{-1})	SD (±)	SE	CI	Cumulative BGWDM (t ha^{-1} year^{-1})	SD (±)	SE	CI
2011	GS2	N/A	N/A	N/A	N/A	4.71	0.55	0.22	0.57
2012	GS3	3.02	0.24	0.1	0.25	7.75	0.53	0.22	0.56
2013	GS4	3	0.16	0.07	0.17	10.73	0.55	0.22	0.58
2014	GS5	2.5	1.22	0.5	1.28	13.22	1.49	0.61	1.56

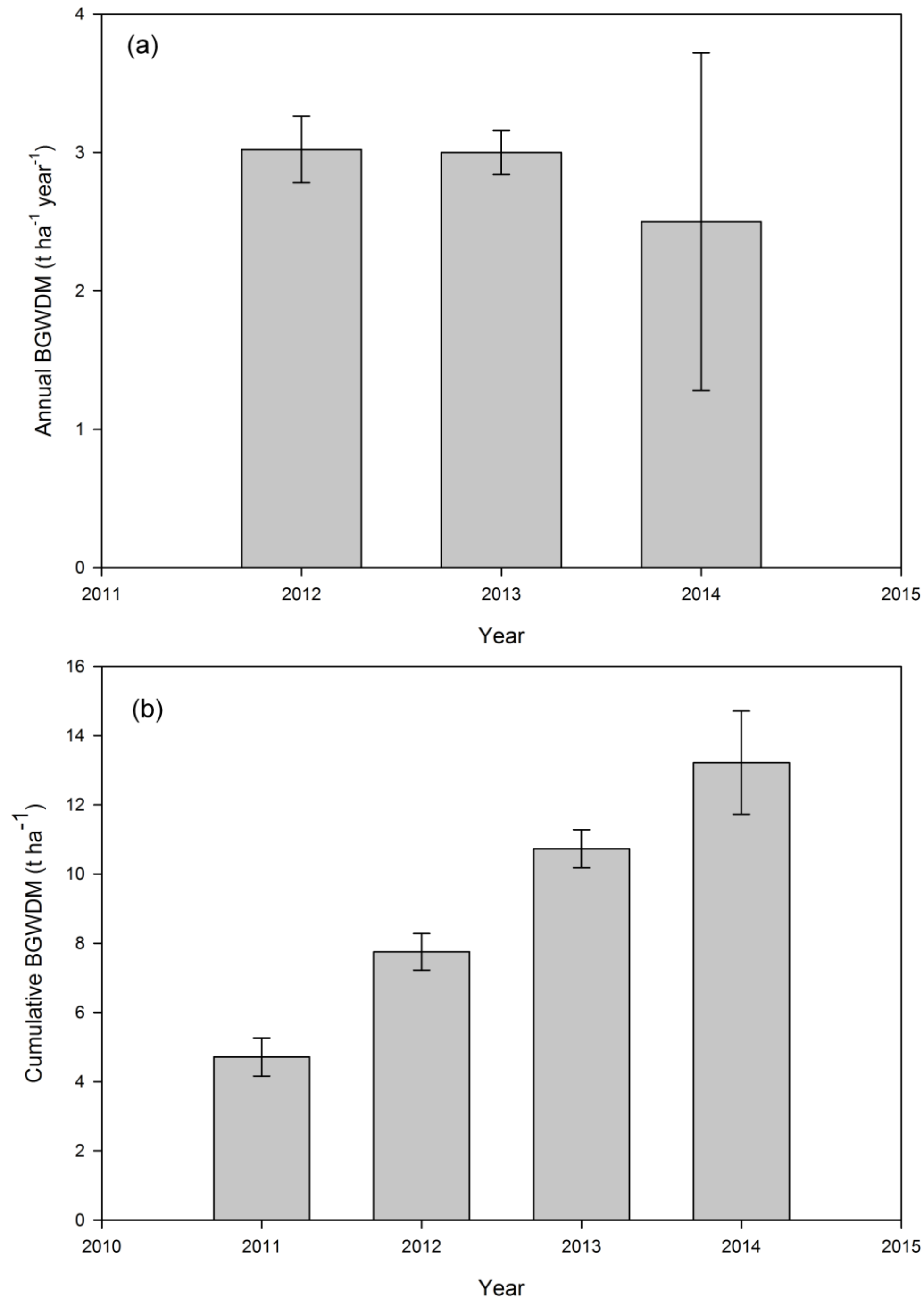

Figure 20: Time course of (a) annual belowground woody dry mass (BGWDM, t ha^{-1} year^{-1}) over three years (2012-2014) and (b) cumulative BGWDM (t ha^{-1}) over four years (2011-2014) study for poplar clone J-105 in a short rotation coppice (second rotation/coppiced established in winter 2009/2010) culture. Mean values of replicates and standard deviations (SD±) are shown by vertical bars.

In the results, annual and cumulative BGWDM were observed where non-significant differences were observed in annual production while significant differences were observed in cumulative production (**Figure 20a & b**). This BGWDM was considerable which represented the second C pool of the SRC system. This long-term BGWDM also contributed to enhance the C sequestration along the four-year sequence (Pacaldo et al. 2014). The value observed for the annual BGWDM was close to the previous study where Berhongaray (2014) observed 2.4 t ha^{-1} $year^{-1}$, however, it was much higher than the 0.90 t ha^{-1} $year^{-1}$ reported for an SRC plantation in Canada (Arevalo et al. 2011). This might be due to the higher planting density in the present study. In annual BGWDM dynamics did not significantly differ, which may be due to well established root systems (total age between 11 to 13 years) while cumulative BGWDM significantly differed, that might be due to the fast growth in first rotation. In this thesis, BGWDM stump (height 15cm) was also considered which might be in disagreement with some other studies due to AGWDM consideration on soil surface (Mokany et al. 2006).

5.5. Growth and biomass determinants

5.5.1. Leaf area index and leaf area development

Indirect LAI measurements through all the growing seasons from GS1-GS4 (2010-2013) were measured by SunScan Plant Canopy. Indirect LAI was validated by direct LAI methods where LAI was directly determined from litter collection which was considered as the true value, and the LAI from the indirect method was then compared and validated against direct method (litter fall collection) in 2009 (uncoppiced, Fischer 2012) and in 2012-2013 in coppiced (Tripathi et al. 2016). In the present study, results are shown for 2012 (coppiced) where regression analysis between direct and indirect measurements of LAI showed strong agreement (R^2=0.83) and highly significant linear correlation (p=0.005, **Figure 21**).

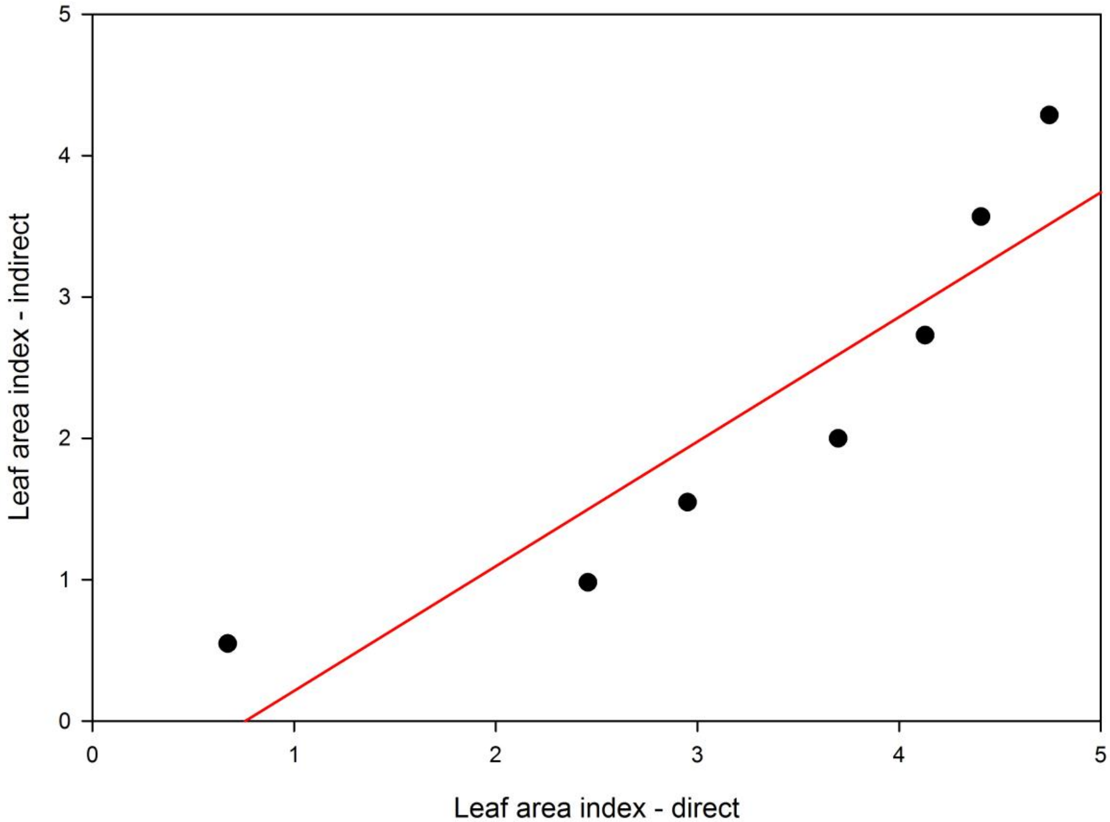

Figure 21: Relationship between indirect (SunScan Plant Canopy Analyzer) measurements of leaf area index LAI) and direct values obtained through litter collections in coppiced short-rotation coppice (SRC) culture in 2012. The relationship is ~1 (R^2=0.83 and p=0.005).

McShane et al. (1983), and Bouriaud et al. (2003) have reported a litter fall direct (non-harvesting direct method) LAI method as one of the most reliable measurements in forest ecosystems. This method could be often used for validation of indirect LAI approaches because it is more accurate (Lovell et al. 2003; Jonckheere et al. 2004a; Liberloo et al. 2004; Thimonier et al. 2010). This direct method is still considered as the best choice for accurate measurements of LAI; however, as this method is time consuming, researchers demand to use alternate indirect methods such as optical hemispherical photography and plant canopy analyzers method (Li 2000/2200 and SunScan). The present study supports to validate (83%) the SunScan Plant Canopy Analyzer for high dense SRC poplar culture which is in agreement with the validation of SunScan plant canopy analyzer for cereal crops (sugarcane) in South Africa and for maize in Nigeria (Chiroro et al. 2006; Oguntunde et al. 2012). In the current study, the results prove that the SunScan Plant Canopy Analyzer method has good potentiality for indirect measurements in SRC poplar plantations (Tripathi et al. 2016). Numerous other techniques have been developed for estimating LAI with the use of optical devices. A review of the indirect and direct methods can be found in Welles & Cohen (1996) and Bréda (2003). The good performance of the SunScan Plant Canopy Analyzer device lends to support the manufacture claim and gives a good estimate of the LAI especially in cereal crops (Potter et al. 1996). This method is an appropriate, reliable, and faster method than the direct method. For most practical purposes, this level of accuracy should be adequate. SunScan Plant Canopy Analyzer assumes that the leaves are green and reflects 25 % of PAR. However, at the end of the growing season, they are not green and reflect more PAR. During some parts of the season they are dark green and reflect less PAR. SunScan Plant Canopy Analyzer also assumes some leaf angle which does not have to be always correct. So there are some uncertainties around all the methods. However, SunScan Plant Canopy Analyzer is resistant to weather changes and allows for a measurement under versatile weather conditions as well.

After successfully validating (Tripathi et al. 2016) the indirect LAI methods, seasonal course of LAI were observed for four growing seasons from GS1-GS4 (2010-2013) using SunScan Plant Canopy Analyzer (**Figure 22**). The development of leaf area during the growing season closely depends on light interception and air temperature.

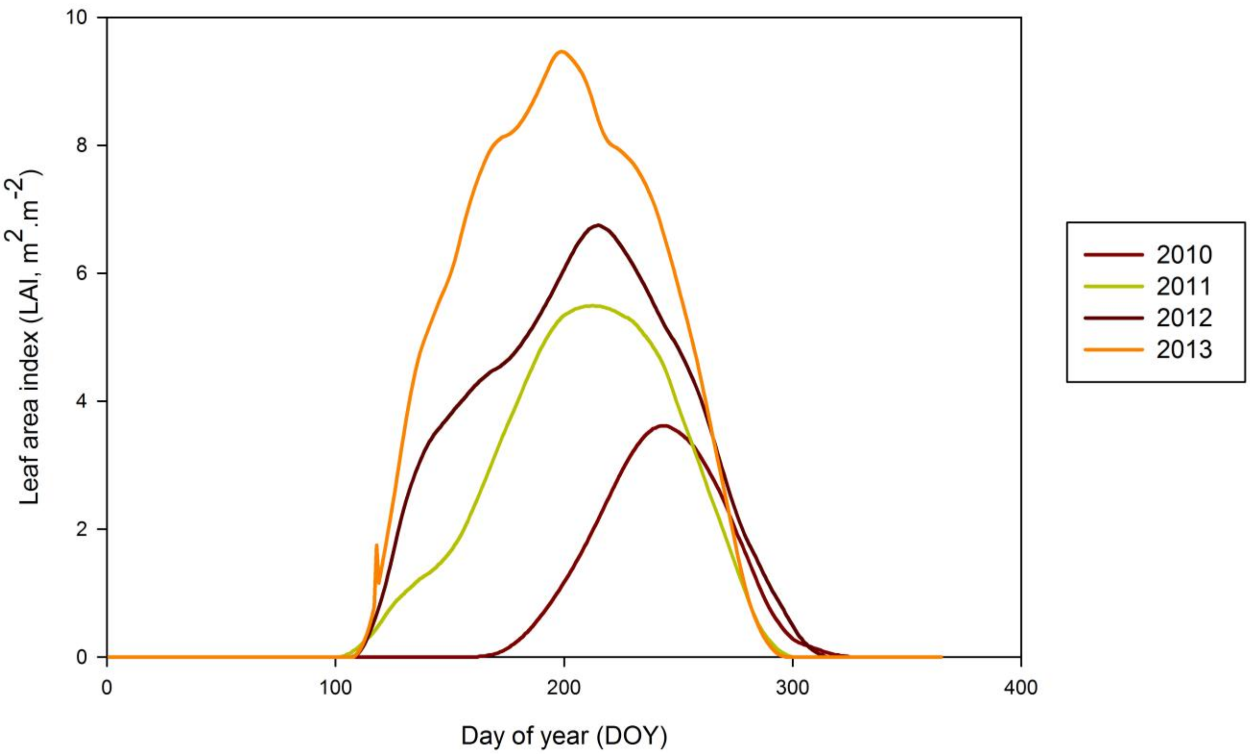

Figure 22: Time course of leaf area index (LAI) measured weekly and biweekly by the SunScan Plant Canopy Analyzer instrument during the growing seasons 2010-2013 (GS1 to GS4) in short rotation coppice (SRC) poplar.

The maximum periodic development of LAI evolution was close to the end of summer representing the indefinite deciduous growth in habit of crops, which has been confirmed in earlier reports for fast growing woody crops (Ceulemans et al. 1996; Howe et al. 2000; Tharakan et al. 2008; Broeckx et al. 2015; Tripathi et al. 2016). The LAI_{max} ranged from 3.6 to 9.5 in different growing seasons from GS1 to GS4 (**Figure 23a**). The lowest maximum LAI (LAI_{max}) of 3.6 was observed in GS1 (after one year of coppiced and total age of stump being nine years) and highest LAI_{max} of 9.5 was reached in GS4 (after four years of coppiced and total age of stump being twelve years). The LAI_{max} increased with the number of growing season because of well-established root systems, height of trees and high density of multi-stem. These results are in agreement with previous studies where LAI_{max} varied within the range of 3.5 to 10, which may be dependent on growing season's weather conditions, localities and varieties of poplar clones (Ceulemans et al. 1990, 1996). On the contrary, Broeckx et al. (2015) have reported LAI_{max} to be varies between 0.5 to 1.7 for one year old (first growing season) and 0.9 to 4.6 in two year old (second growing season) diverse poplar clones at Flanders in Belgium while in other fast growing trees like eucalyptus and willows forest types, LAI_{max} values was estimated to vary from 0.8 to 6.1 and from 2.4 to 6.7, respectively (Ceulemans et al. 1990; Bonhomme 2000; Howe et al. 2000; Tharakan et al. 2008). Such variations in LAI_{max} values depends on varieties of cultivars, site specificity, length of the growing season, plant density, temporal and spatial variability, availability of water and nutrients. They may also depend on the physiology of the genotypes (Watson 1947; Ceulemans et al. 1996). On the contrary, LAI_{max} could be even lower than the values obtained in present study due to the limited precipitation in that particular region; moisture deficiency could reduce growth, leaf traits, yield and yield components (Anderson 1983; García et al. 2003).

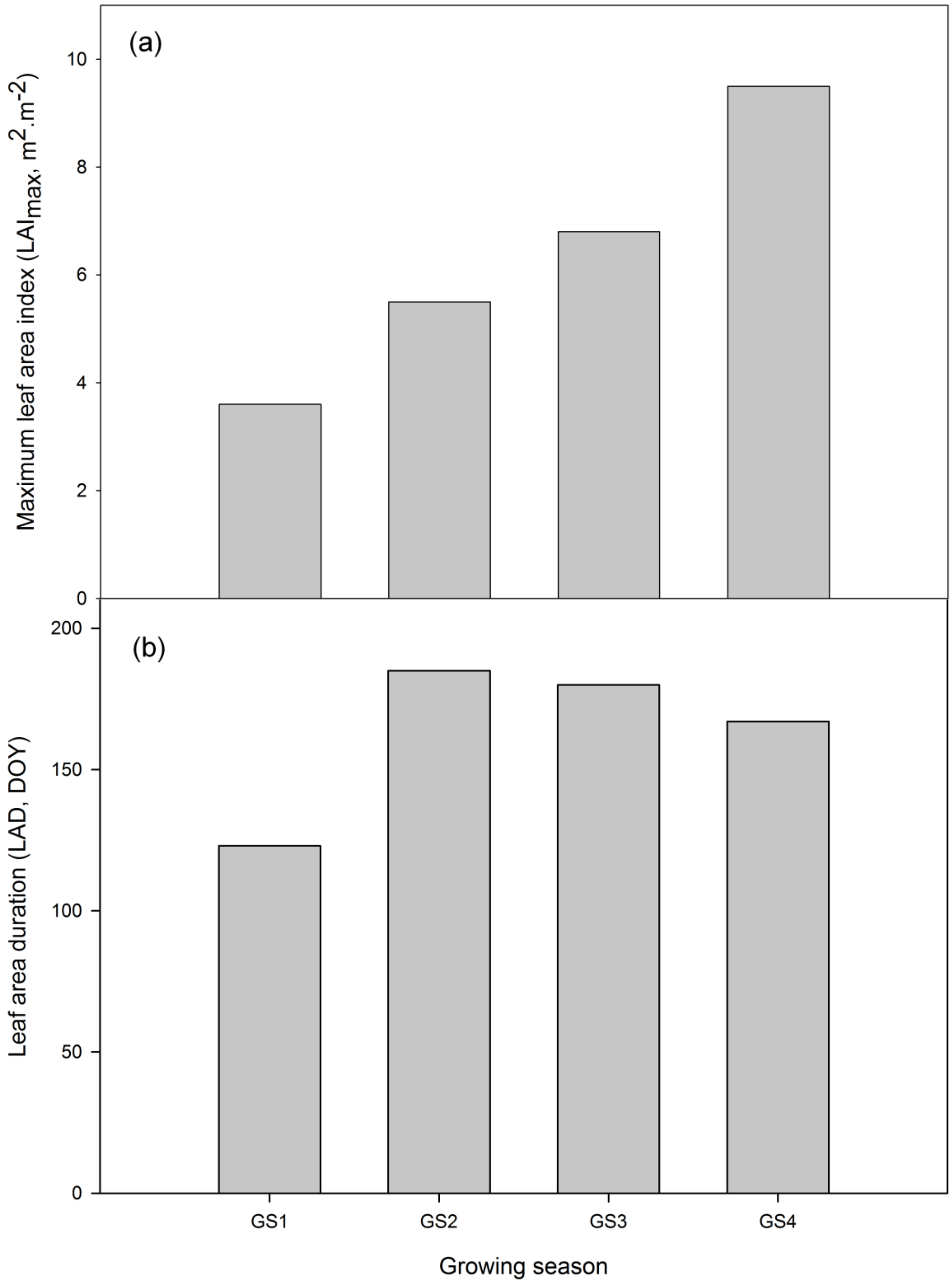

Figure 23: Vertical bars show relationship between (a) LAI_{max} and growing season (GS) and (b) leaf area duration (LAD) and growing season (GS) from 2010-13.

After LAI evolution, LAD was studied which is an important parameter to define the plant physiology and is interconnected to LAI development and biomass. In SRC poplar, LAD for different growing season is shown in **Figure 23b**. Maximum LAD (185 days) was observed in GS2 (total age of stump was ten years) and minimum LAD (123 days) was observed in GS1 (total age of stump was nine years). LAD may have increased in GS2 due to its dependency on increased LAI_{max} and growing season. LAI_{max} and LAD could be strongly dependent on each other which may have important roles in determining wood or biomass production in crops **(Figure 24**). LAD is also important for leaf area development.

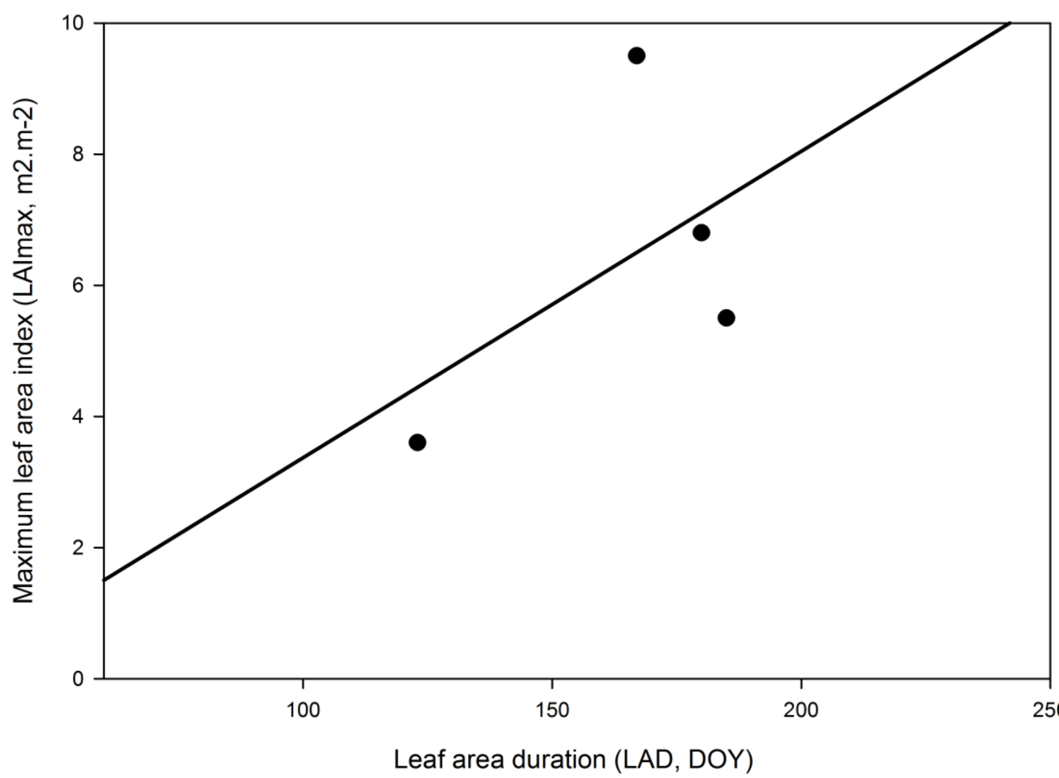

Figure 24: Linear regression between leaf area duration (LAD) and maximum leaf area index (LAI_{max}) where R^2=0.53.

This study is similar to previous study where LAD range varied between 128 to 149 days for poplar clones on former pasture land in Missouri River floodplain area, USA (Dowell et al. 2008), however, it also varied in a wide range between 41 to 148 days for twelve poplar genotypes on former agricultural crop and extensively grazed pasture land in Flanders, Belgium (Broeckx et al. 2015). LAD could be varied in different growing seasons, crop genotypes and former land use.

5.5.1.1. Relationship between leaf area and woody dry mass production

At the end of each growing season, the aboveground standing woody dry mass was estimated through an intensive diameter inventory (more details in chapter 4 section 4.2.3.1). Dry mass has been estimated from diameter measurements using allometric relationships between stem diameter and AGWDM. In the present study, for correlation between the seasonal LAI_{avg} vs. annual AGWDM, seasonal LAI_{max} vs. AGWDM and LAD vs. AGWDM linear regression was plotted as shown in **Figure 25**, where coefficient of determination (R^2) values for three correlations were R^2=0.90, R^2=0.91 and R^2=0.82, respectively.

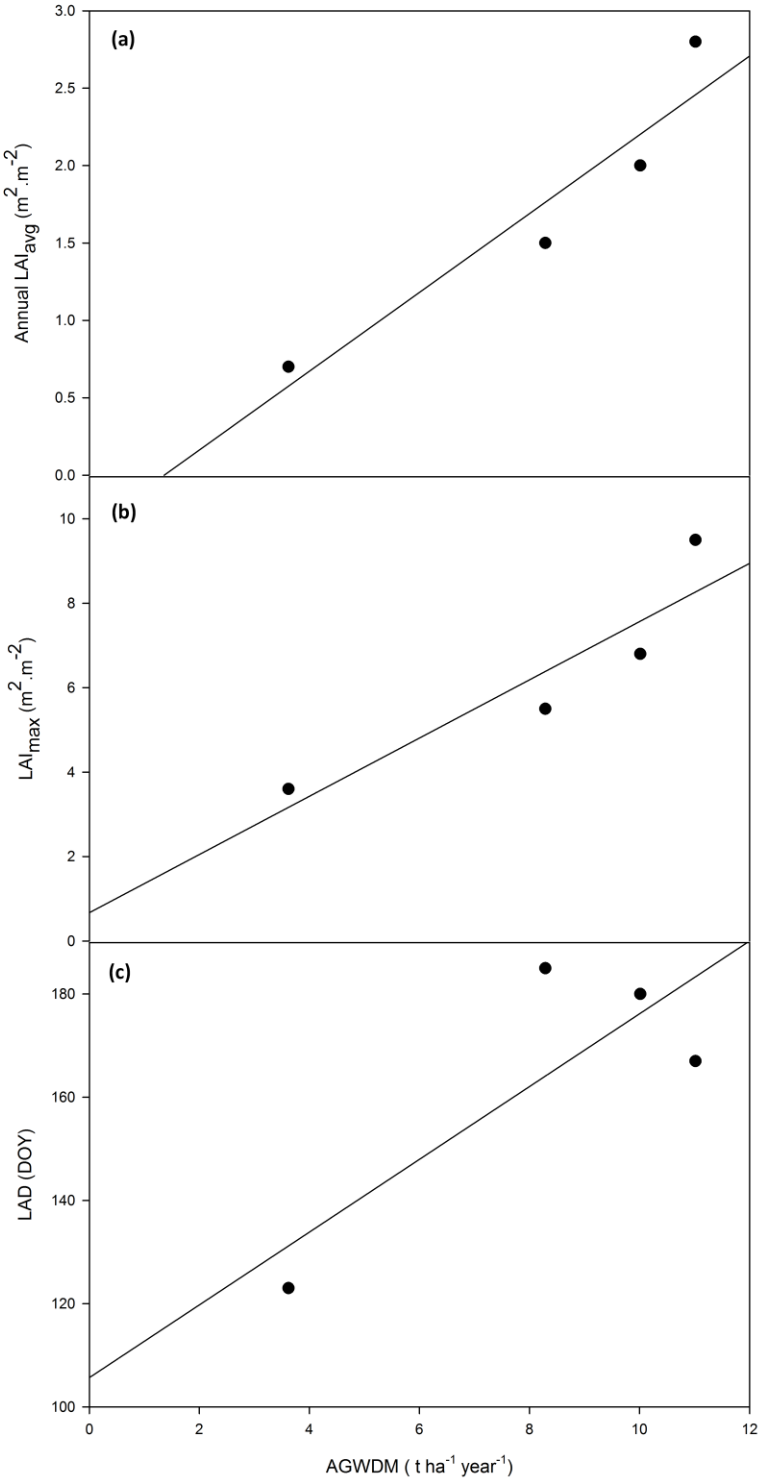

Figure 25: Relationship between (a) annual average leaf area index vs. annual aboveground woody dry mass (AGWDM), (b) maximum leaf area index (LAI_{max}) vs. AGWDM and (c) leaf area duration (LAD, DOY) vs. AGWDM from 2010-2013 (GS1 to GS4) in coppice poplar culture.

In the present results, LAI and LAD show positive correlation between AGWDM (R^2 values ~1, **Figure 25**). It means AGWDM is strongly dependent on annual LAI_{avg}, LAI_{max} and LAD. LAI_{avg}, LAI_{max} and LAD could be good indicators of aboveground woody dry mass production in SRC poplar genotypes. These results confirm the earlier observations of positive strong correlation between LAI_{avg}, LAI_{max}, LAD and AGWDM in high density poplar genotypes (Ceulemans et al. 1990; Barigah et al. 1994; Orlović et al. 1998; Tharakan et al. 2005; Broeckx et al. 2012, 2015; Verlinden et al. 2013; Tripathi et al. 2016) which can be considered as a useful trait for the early selection of high productivity in poplars (Ceulemans et al. 1994; Bunn et al. 2004). As it was previously demonstrated for several poplar genotypes (Ridge et al. 1986; Barigah et al. 1994; Harrington et al. 1997), individual leaf area was also positively correlated with biomass production, though less pronounced as LAI.

5.5.2. Radiation use efficiency (RUE)

RUE is another main determinant of AGWDM in SRC poplar genotypes, willows and trees (Ceulemans et al. 1996, Linderson et al. 2007; Kinry 1998, Broeckx et al. 2015). For poplar clone J-105 average RUE was 1.1 g MJ^{-1} for four years duration in coppiced (GS1 to GS4). Maximum RUE was 1.3 g MJ^{-1} in GS4 after four years of coppice (total age of stump was thirteen years). RUE increased with increase in the number of growing season due to well established root system, dense canopy and high plant growth (**Figure 26**).

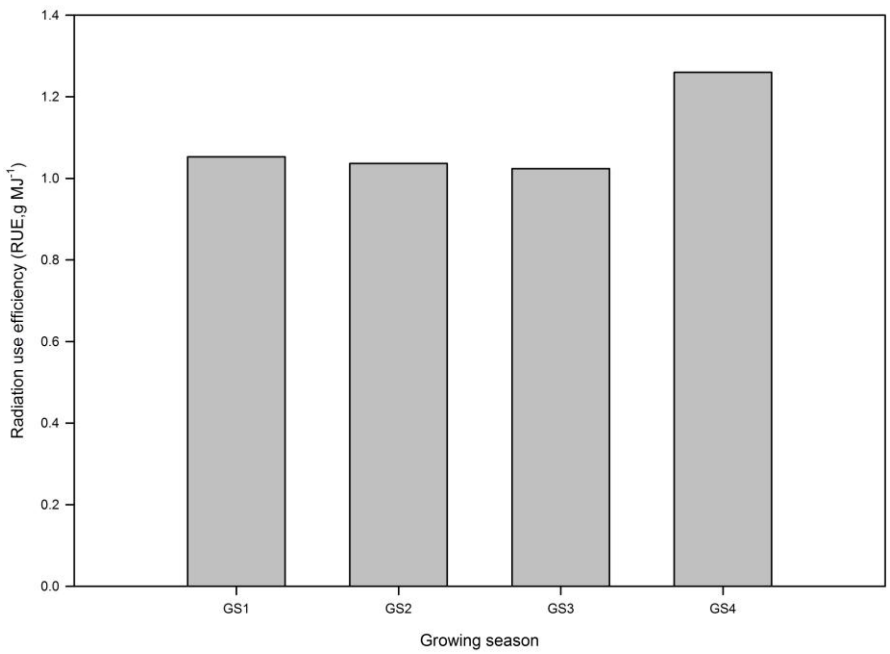

Figure 26: Relationship between growing season (GS) and radiation use efficiency (RUE, g MJ^{-1}) from 2010-2013 (GS1-GS4) in poplar clone J-105 under SRC management.

In the present study, RUE for fast growing SRC poplar is reasonable compared to Linderson et al. 2007, who estimated RUE to be 1.40 g MJ^{-1} for willow clones in Scania, the southernmost province of Sweden and in some studies for poplar plantations, RUE varied between 1 to 2 g MJ^{-1} (Cannell et al. 1988; Landsberg & Wright 1989;Green et al. 2001). Unlikely, Broeckx et al. (2015) have reported RUE values to be varied between 0.29 and 0.68 and average RUE to be 0.50 g MJ^{-1} in twelve polar clones in Flanders, Belgium. Such a low RUE values are characteristics of site specificity, length of growing season, height and age of trees and also based on genotypes. A variety of RUE values have been reported for poplar plantations. However, maximum RUE of 3.0 g MJ^{-1} was reported for poplar experimental trials in Scotland (Cannell et al. 1988). Generally RUE values were high due to good water availability and rich source of nutrients but lower RUE values were reported for an irrigated and fertilized clonal stand of poplars in U.S.A. (Landsberg & Wright 1989).

5.5.2.1. Relationship among RUE, woody dry mass production and leaf area

The correlation between the RUE vs. AGWDM, RUE vs. LAI_{max} and RUE vs. LAD for four GS (from GS1 to GS4) are observed. RUE has moderate positive correlation with AGWDM, where R^2=0.50 (p=0.52) while RUE has a strong relationship with LAI_{max}, where R^2=0.80 (p=0.21). Negative correlation was observed between RUE and LAD, where R^2= -0.017 (p=0.98) (**Figure 27**). Non-significant differences was reported because p>0.05 was considered.

In SRC poplar clone J-105, RUE could be reliable determinants of AGWDM production, however, RUE has a strong correlation with LAI_{max} as in the above mentioned results (chapter 5 section 5.5.2.1), where we observed a strong positive correlation of LAI_{max} with AGWDM, which implies that RUE and LAI_{max} are interconnected. The results confirm earlier observations of positive correlation of RUE and AGWDM in high density poplar genotypes (Kiniry 1998; Green et al. 2001; Broeckx et al. 2015b). These results suggest that biomass could be improved by selecting poplar genotypes for specific growth parameters thus considering planting density, and consequently RUE is taken into account.

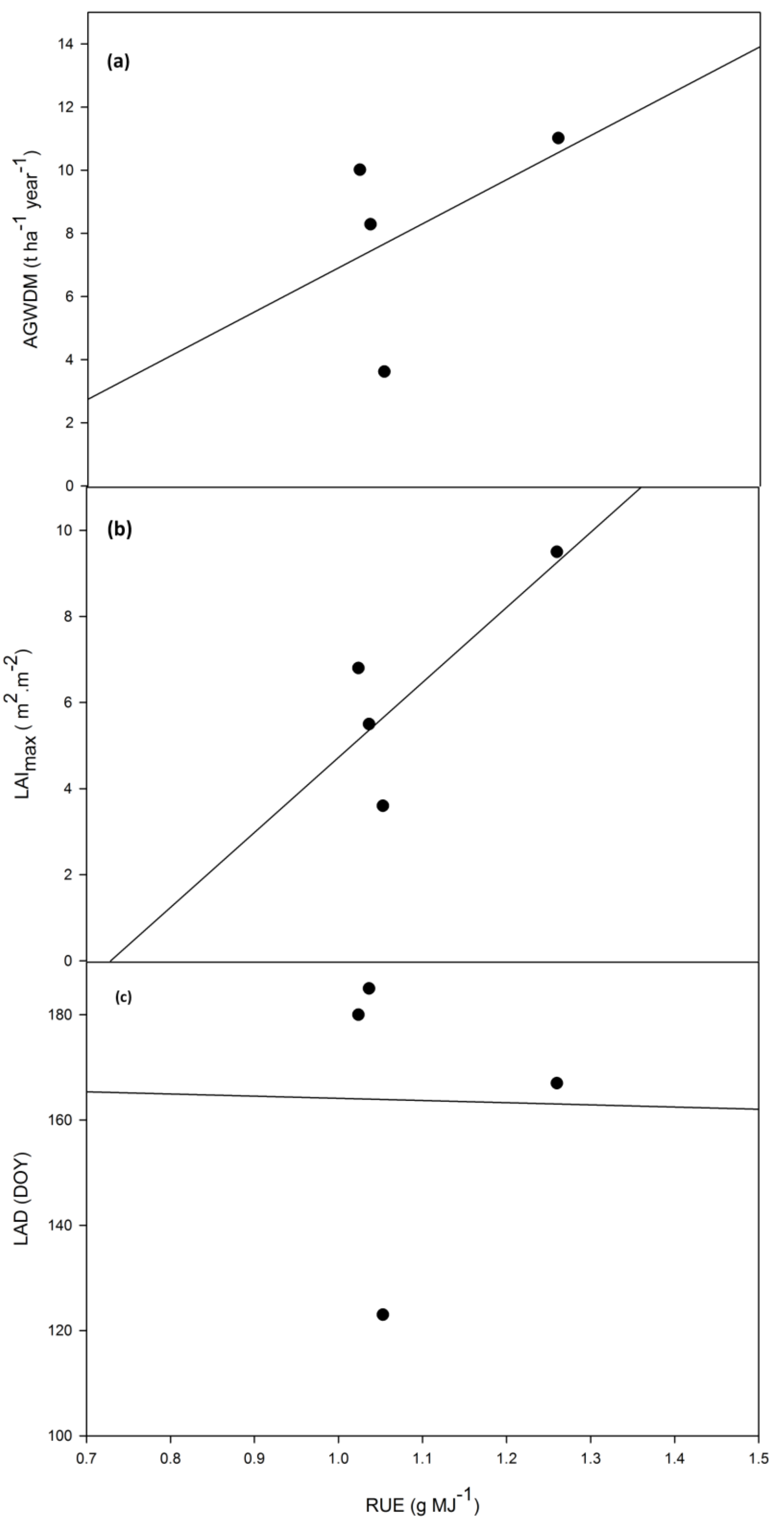

Figure 27: Relationship among radiation use efficiency (RUE, g MJ^{-1}), (a) aboveground woody dry mass (AGWDM, t ha^{-1} $year^{-1}$), (b) maximum leaf area index (LAI_{max}, $m^2.m^{-2}$) and (c) leaf area duration (LAD, DOY).

6. Conclusions

The first part of the study focused on developing a site specific power allometric equation for poplar clone J-105 on former agricultural land to estimate the standing AGWDM with fertilizer and non-fertilizer treatments under SRC management. Developments of precise, non-destructive allometeric equations are important to allocate the above and belowground standing woody dry mass to ensure the sustainability and low cost methods. From this study, it can be concluded that the allometric equation thus developed may be considered as a site specific or universal equation for woody dry mass allocation for poplar clone J-105.

In the second part of the study, there was no effect of fertilizers on woody dry mass accumulation of regrowth on former agricultural land in SRC coppice management. The poplar clone J-105 of shoots per stump, mortality of stools as well as the production of woody dry mass showed no significant difference across any of the treatments, thus, showing no benefit of fertilization to cultivate fast growing trees on former agricultural land in SRC management. Annual AGWDM may increase with the certain number of growing seasons, or it may decrease or remain constant after six years of plant growth in coppice rotation. In the present study automatic thinning was observed with increasing the number of growing season. Maximum stool survival rate was observed in GS2 and minimum was in GS5.

Third part of the study concluded that maximum annual BGWDM to be in GS3. It may be decreased after the well establishment of the root systems after a certain period such as twelve to fifteen years in poplar under SRC management.

Fourth part of study concluded that SunScan Plant Canopy Analyzer (indirect LAI method) is an appropriate and portable instrument for *in situ* LAI estimation in high-density short rotation coppice culture of poplar. The most accurate and precise results were obtained, when the indirect (SunScan Plant Canopy Analyzer) and direct measurements (litterfall collection) were compared and successfully validated. The methodology presented can be applied for rapid and reliable indirect LAI measurements in homogenous canopy row crops. This indirect quantitative estimation of LAI may further be correlated to photosynthetic rate, canopy physiology and water use efficiency.

Fifth part of study concluded that the dynamics of LAI assessment against plant age can help in standardizing plant spacing and pruning requirement for optimizing tree architecture. During the four years of LAI measurements in coppiced (GS1 to GS4), maximum LAI was reported in GS4 when trees reached maximum height and maximum canopy closure were observed. Maximum RUE was observed in GS4 when maximum AGWDM and LAI_{max} were reported. LAI and LAD could be a strong determinant of AGWDM for poplar clone J-105 in coppice rotation while RUE to be a moderate determinant of AGWDM in poplar clone J-105 but the relationship (in the present thesis) observed between RUE and $LAI_{max,}$ is a strong relationship (R^2=0.80) obtained, implying both are interdependent. \

Overall LAI, LAD and RUE could be good estimator of AGWDM in SRC poplar clone J-105 but this thesis has some limitation to study the other parameters such as nitrogen because of a time frame.

For more accurate and depth knowledge of SRC poplar clone J-105 on former agricultural land in Czech Republic long term study is required and also one needs to focus on other parameters such as nutrient and water use efficiency.

7. Závěr

Tato první část studie je zaměřena na rozvíjející se a všeobecně použitelnou alometrickou rovnici pro klon topolu J-105 na původní zemědělské půdě, která má potenciál použití pro odhad stávajícího AGWDM při použití hnojiv či bez jejich aplikace. Z této studie může být závěrem shledáno, že tato alometrická vyvinutá rovnice může být považována za univerzální rovnici pro klon topolu J-105.

Ve druhé části této studie nebyl prokázán žádný vliv užití hnojiv na další růst a akumulaci biomasy na původních zemědělských půdách, . Bylo stanoveno, že pozitivní vliv v užívání hnojiv na rychlý růst stromů na původně obdělávaných zemědělských půdách, je skutečně marginální.

Ve třetí části studie bylo stanoveno, že maximální roční BGWDM je u GS3.
Ve čtvrté části studie bylo stanoveno, že tzv. SunScan Plant Canopy analyzátor (nepřímá LAI metoda) je vhodným nástrojem, který může být použit pro odhad LAI v hustě rostlých kulturách topolu. Tato prezentovaná metodologie může být použita pro rychlá spolehlivá a nepřímá měření Tento nepřímý kvantitativní odhad LAI může dále být v korelaci k rychlosti fotosyntézy, fyziologii a efektivitu v užívání vody.

Pátá část studie stanovila, že dynamika LAl pro hodnocení vlivu stáří stromů může pomoci ke standardizaci rozmístění na stromů na ploše a požadavkům na probírku při optimalizaci architektury porostu.

Maximální RUE bylo pozorováno u varianty GS4, kdy stanoveny maximální hodnoty AGWDM a LAI_{max}. LAI a LAD by mohly být silnými determinanty AGWDM u klonu topolu J-105 tu, zatímco RUE je mírným determinantem AGWDM u klonu topolu J-105. Nicméně byl nalezen vztah mezi RUE a $LAI_{max,}$ Obecně LAI, LAD a RUE by mohly být dobrými veličinami predikce AGWDM u SRC u klonu topolu J-105.

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9. Appendix

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10. Curriculum vitae

Personal information

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Date of birth:	5th February, 1987
Nationality:	Indian
Permanent address:	Kasba-Khas, Ghosi 275105, Mau, UP, India
Current address:	Bělidla 986/4a, Brno 60300, Czech Republic
Languages known:	English, Czech, Hindi
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Education & training

- Ph.D. Forest Ecology and Landscape Engineering (2011-till now). Department of Forest Ecology, Faculty of Forestry Mendel University in Brno, Czech Republic
- M.Sc. Forestry (2010) from Forest Research Institute Deemed University (ICFRE) Dehradun, Uttarakhand, India. www.friuniversity.edu.in, www.icfre.org
- GIS & GPS Certificate Course (2009) Indian Institute of Remote Sensing (IIRS), Dehradun, ISRO (NRSC), India
- 4th EuroCoppice Training School "Coppice Management, Biodiversity and Services" from 17th-23rd July 2016. Organized by the Albert-Ludwigs University of Freiburg in cooperation with the Forestry District of Rhineland-Palatinate Boppard, Germany
- EuroCoppice STSM from 31st May to 21st June 2016 to group Plant & Vegetation Ecology, Department of Biology, University of Antwerp, Antwerp, Belgium
- Completed two months Erasmus practical traineeship (1st December 2014-31st January 2015) from Department of Biology, University of Antwerp, Antwerp, Belgium
- Attended Ecophysiological Measurements summer school (30th September – 4th October 2013), Beskydy Mountain, organized by Global Change Research Centre Brno Czech Republic

- Attended Inter-Drought summer school (16th – 22nd June 2013), Telč in Czech Republic.
- Attended Ecophysiology Techniques Workshop (10-15th September 2012), Lisbon, Portugal organized by Cambridge University of London
- Attended LI-COR Eddy covariance training course from university of BOKU, Vienna, Austria (2012)

Professional experience

- Researcher (since January 2016) at Global Change research Institute (CzechGlobe) AV ***ČR*** v.v.i., Brno, Czech Republic
- Researcher (August 2011-Decemebr 2015) at Global Change research Centre (CzechGlobe) AV ***ČR*** v.v.i., Brno, Czech Republic
- Researcher (November 2014-June 2015) at Department of Agro-systems and Bioclimatology, Faculty of Agronomy, Mendel University, Brno, Czech Republic
- Junior consultant (December 2010-July 2011) at Carbon Credit World and Green route Environ Pvt. Ltd. Gurgaon, Haryana, India in green energy and CDM projects
- Research Associate (July 2010-November 2010) at Institute of green economy New Delhi, India in field of Climate Change, Ecological aspects, Renewable Energy, Bio-fuel projects

Grants

- Cost Action for summer training school approved (traveling grant)
- Cost Action for short term scientific mission (STSM) approved (traveling grant)
- Erasmus Plus (traveling grant)

IGA project at Faculty of forestry and wood technology, Mendel University in Brno (2014) entitled "Study of below ground biomass in short rotation poplar coppice J-105 in the Moravian highlands"

Presentations

Oral:

- Adaptation to Climate Change (Micro) in Agroforestry systems. 2nd Global Submit on Plant Science 6-8 October 2016, Crowne Plaza, Heathrow, London, UK
- Long Term Measurement of Leaf Area Index and Radiation Use Efficiency in Short Rotation Coppice Poplar Culture and Cereal Crops. 24th European Biomass Conference & Exhibition (EUBCE) 6-9 June, Amsterdam, Netherlands
- Micro-climate modifications in agroforestry systems presented as a keynote speaker in Indian Ecological Society: International Conference "Natural resource Management: Ecological perspectives " Sher-e-Kashmir University of Agricultural Science & Technology of Jammu, India , 18th-20th February 2016
- Climate Change and Sustainability presented as a invited lecture Forest Research Institute Deemed University, UK, India 23rd February 2016
- Climate Change and Sustainability presented as a invited lecture Ewing Christian College University of Allahabad, UP, India 27th February 2016
- Estimation of total biomass of a short rotation coppice poplar clone in South Moravia, Czech Republic presented at PLECO, University of Antwerp, Belgium 9th January 2015

Posters:

- Dynamics of biomass production in poplar clones grown under short rotation coppice management in the Czech Republic. Coppice Forests in Europe Conference 15-17 June 2016, University of Antwerp, Antwerp, Belgium
- Comparison of leaf area index development and radiation use efficiency of a poplar short rotation coppice culture and cereal crops. The Towards Climatic Services Nitra Conference 15-18 September 2015, Nitra, Slovakia
- Assessment of leaf area index development and radiation use efficiency of a short-rotation coppice culture with poplar clone J-105. Conference proceeding "Global Change: A Complex Challenge 2015

- Effect of drought on fine roots productivity in poplar-based short rotation coppice. EGU General Assembly 2015
- 3rd annual conference "Global Change and Resilience" 22-24 May 2013, Brno, Czech Republic
- Radiation use efficiency of above- ground woody biomass productivity of poplar clone J-105 (*Populus nigra* × *P. maximowiczii*) in Czech Moravian Highlands.
- The aboveground biomass allocation in the hybrid poplar clone (Populus nigra x P. Maximowiczii) grown as a short rotation coppice. Ecophysiology Techniques Workshop 10-15 September 2012, Lisbon, Portugal.

Conferences:

- 2nd Global Submit on Plant Science 6-8 October 2016, Crowne Plaza, Heathrow, London, UK
- Coppice Forests in Europe Conference 15-17 June 2016, University of Antwerp, Antwerp, Belgium
- 24th European Biomass Conference & Exhibition (EUBCE) 6-9 June, Amsterdam, Netherlands
- Indian Ecological Society: International Conference "Natural resource Management: Ecological perspectives at Sher-e-Kashmir University of Agricultural Science & Technology of Jammu, India 2016
- European Geoscience Union at Vienna 2015
- Global Change "A Complex Challenge" at Global Research Centre Brno 2015
- SilvaNetWoodNet at Mendel University in Brno 2014
- Global Change and Resilience at Global Research Centre Brno 2013
- MendelNet at Mendel University in Brno 2012
- International conference on science communication at University of Lorrain, Nancy, France 2012
- Global Ecosystems, biodiversity and environmental sustainability in the 21st century at Department of ecology and environmental science Assam University, India 2012

Workshops

- State-of-the-art drought monitoring methods and the art of sharing it with the stakeholders 9th Feb-12th Feb 2015 Brno, Czech Republic
- 9th International Workshop on Sap Flow, June 4-7th, 2013, Ghent Belgium
- Eddy Covariance workshop in Helsinki 2012

Selections

- Selected for Swiss Climate Summer School 2016, Oeschger Centre, Falkenplatz 16, CH-3012 Bern, Switzerland