The Lord of the Willow Rings

A study on the effects of biomass harvesting in natural willow rings around prairie wetlands

Thesis research at the Agroforestry Development Centre
Indian Head, Saskatchewan, Canada

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FOREWORD

This research was conducted as a Bachelor thesis research project for the education program Forest and Nature Management at University of Applied Sciences Van Hall Larenstein, the Netherlands. The research topic has been provided by the Agriculture and Agri-Food Canada Agroforestry Development Centre (ADC) located in Indian Head, Saskatchewan, Canada.

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ABSTRACT

The increased interest in using woody biomass as a carbon neutral renewable resource for energy production has been a result of the growing awareness of CO_2 emissions from burning fossil fuels. A great potential for production of woody biomass in the Prairie Pothole Region was found in willow rings surrounding prairie wetlands. The Biobaler designed by Anderson group in 2006 makes harvesting of willow rings possible. Harvesting of willow rings with a biobaler for biomass production is currently only implemented by the Agroforestry Development Centre in Indian Head, Saskatchewan. Due to the early stage in which the system is situated limited research has been carried out on important aspects regarding this topic.

As a result of the combination of implementing literature reviews, interviewing the biomass expert at the Agroforestry Development Centre, implementing field experiments and doing calculations it was possible to get a good understanding of the current status of willow ring harvest and what recommendations to give for the future.

The objectives of this study were to determine the regeneration, yield and mortality of native willows after harvesting of natural willow rings, to set up management tactics to increase the efficiency of the system and to determine if the Pyrot 300 wood-fired boiler is capable of handling shredded willow biomass.

Significant variation was found in herbaceous matter content in biobales from the three willow rings. Biobales from the first and second time harvested willow rings (WR #1 and WR #2) contained significantly less herbaceous biomass than biobales from the third time harvested willow ring (WR #3) ($p=0.0008$ and $p=0.0001$ respectively). The variation between WR #1 and WR #2 was also found to be significant ($p=0.039$) where biobales from WR #1 contained more herbaceous biomass than biobales from WR #2. Herbaceous content varied from 2.38% to 10.74% dry weight. The content of herbaceous matter in biobales can likely be reduced by implementing certain management practices; however, variations between willow rings will always occur.

The effect of harvesting on regeneration of shoots was determined at the beginning of the growing season. An increase in the number of shoots regenerated per m^2 was found by an increase of applied harvests; however, the variance is found to be not significant.

At the end of the growing season the mortality of shoots and total yield was determined.The overall shoot mortality of WR #1 was calculated at 92.01%, WR #2 at 81.52% and WR #3 at 69.06%. This mortality of shoots has predominantly taken place during an early stage of the growing season and was likely caused by long-time inundation. Abnormal precipitation caused high mortality rates between initial budding in May and shoot survival in October. The total average annual biomass yield found in the three willow rings ranged from 0.89 to 1.48 odt ha^{-1} y^{-1}.

With the information gathered on the herbaceous content of biobales in combination with data on moisture contents the characteristics of biomass from willow rings was determined. Experiments showed that shredded biomass from each willow ring reacted different during combustion. In certain cases the characteristics of the biomass did not did not match the qualifications of the wood-fired boiler which resulted in a number of difficulties. The production of high quality biomass is possible with the system designed at the ADC; however, it was concluded that modifications to the KÖB Pyrot 300 are required to improve its capability of handling shredded willow biomass.

Calculations to the costs of producing wood shreds from biomass derived from natural willow rings have showed that the cost of biomass is about 9% lower per GJ than natural gas. Even greater financial savings can be made when propane, diesel or electricity are replaced by biomass. The costs of biomass will increase when more use is made of custom work.

A variety of recommendations have come forth out of this research. The recommendations concern the required changes to the wood-fired boiler, drying of biobales, increasing biomass quality, harvesting intensity and harvesting other sources of biomass.

It is my believe that biomass derived from natural willow rings is a promising substitute for fossil fuels in the Prairie Pothole Region.

Table of Contents Page

ABBREVIATIONS

ADC	Agroforestry Development Centre
BTU	British Thermal Unit
DW	Dry Weight
FW/h	Fresh Weight per Hour
GJ	Gigajoule
HP	Horsepower
kW	Kilowatt
odt	Oven Dry Ton
PPR	Prairie Pothole Region
PTO	Power Take-Off
RPM	Revolutions Per Minute
RES	Renewable Energy Source
SRC	Short Rotation Coppice

1 INTRODUCTION

1.1 Background of the study

The growing awareness in recent decades of the emission of CO_2 from burning fossil fuels has increased the interest in using 'carbon neutral' renewable resources for energy production. Woody biomass is a prime example of a renewable resource, which is close to 'carbon neutral'. This means that during the production of energy from biomass the largest percentage of the carbon released to the atmosphere consists of carbon that has been stored in the plant during its growth cycle (Sims, 2006).

In many studies the contribution of biomass as a future source of global energy are predicted to increase in importance. According to these studies the role of woody biomass crops in the production of energy will become crucial (Berndes, 2003).
For example the European Union has set the target for 2020 to produce 20% of the total demand for energy used for heating and cooling from Renewable Energy Sources (RES). In 2008 only 10% of this energy consumption was represented by RES. Biomass (solid, biowaste and bioliquid) has, and will continue to have in the future, a dominant role in the production of RES for heating and cooling. In 2020 biomass is expected to represent 17.2% of the energy produced for heating and cooling (EREC, 2011).

The production of woody biomass through energy crops on plantations is an internationally applied method and is currently applied on several plantations located across Canada. In northern temperate regions willow *(Salix spp.)* and hybrid poplar *(Populus spp.)* are the most commonly used woody energy crops, in warmer climates eucalyptus *(Eucalyptus spp.)* is more common. These three species each exhibit characteristics which make them ideal for woody crop systems; e.g. high yield potential, ability to re-sprout after harvesting and a broad genetic base which increases the potential for genetic improvement (Zhu, 2011).

Short-rotation plantations make use of the ability of these species to re-sprout after harvesting; by leaving the stool and the root system intact crops can be harvested multiple times with short rotations (generally 10 years or less for poplar, four years or less for willow). This system is known as Short Rotation Coppice (SRC). This system requires specific management practices to produce high yields over multiple harvesting rotations. This include, but is not limited to, intensive site preparation, the use of weed control during crop establishment and the input of nutrients after harvests. A frequently discussed downside of plantations is that they are often located on land that is suitable for the production of food.

Across the northern glaciated plains of North America thousands of small wetlands are present. These small wetlands are commonly referred to as “sloughs” or “potholes” and are often surrounded by a mix of shrubs and herbaceous plants. The dominant species within the woody vegetation is willow *(Salix spp.)*. For this reason these wetlands surrounded by woody vegetation are commonly referred to as “willow rings”. Besides the important functions of willow rings on surface and subsurface hydrology and wildlife habitat, willow rings have a great potential as a renewable energy feedstock.

The limited availability of commercial technology for harvesting woody crops has been a limiting factor on small scale SRC biomass harvesting. The most commonly used machine for harvesting SRC was a modified self-propelled silage harvester. This machine cuts the woody stems and feeds them through a chopper where they then are transformed into chips. Harvesting practices that rely on these machines have high harvest capacity - according to Spinelli (2009) an average of 35t Fresh Weight per hour (FW/h). However, they require several additional tractors (for direct transport of the chips), a large financial

investment (> $500.000) and they are not suitable for uneven terrain on which natural willow stands are often found.
In 2006 an alternative to the self-propelled forage harvester was developed to harvest cultivated willow stands in short rotation plantations. The machine was based on an agricultural round baler; “the machine cuts, shreds and compacts the woody stems into a round bale” (Savoie, 2010). Though the hourly yield of this machine is substantially lower (8 to 12t FW/h) than the modified self-propelled forage harvester, no additional tractors are needed during harvest and the financial investment is drastically lower.
However, this prototype biobaler was unsuitable for uneven and/or rocky terrain on which natural willow rings are found. In 2006, further modifications were made to the prototype biobaler that made it suitable for removing natural stands of woody vegetation occurring on uneven and/or rocky terrain.

Research on biomass harvest from natural willow rings around prairie wetlands, concluded that natural willow has a calorific value “essentially equal to ‘conventional’ produced wood chips or purpose-grown willows” (Schroeder, 2009). The results of the combustion tests showed that natural willow had a calorific value of 19.6 MJ kg^{-1} Dry Weight (DW). After harvest with the prototype biobaler, an average first year regeneration of 3.5 ton ha^{-1} DW of native willow was recorded. Biomass harvest from willow rings with a rotation cycle of 4- to 5-years was expected to be feasible.

The thousands of willow rings located across the prairie pothole region (PPR) could be a significant source of biomass production. Additional research is needed to study impacts of harvesting natural willow rings with the Anderson Biobaler. The effects of willow ring harvest with an Anderson Biobaler on avian population health and diversity are currently being researched by a Masters student of the University of Regina.

1.2 Framework

This research was conducted as a Bachelor thesis research project for the education program Forest and Nature Management at University of Applied Sciences Van Hall Larenstein, the Netherlands. The research topic has been provided by the Agriculture and Agri-Food Canada Agroforestry Development Centre (ADC) located in Indian Head, Saskatchewan, Canada. The ADC conducts research to increase knowledge of design and functions of agroforestry systems in Canada.

1.3 Research questions

The objectives of this study are: (1) study the effects of repeated biomass harvest with an Anderson Biobaler from natural willow rings around prairie wetlands on the regeneration characteristics of native willows and (2) develop management practices that increase the efficiency of the system.
I have therefore set up the main research questions as follows:

1. *What are the effects of repeated biomass harvest with an Anderson Biobaler from natural willow rings around prairie wetlands on the regeneration characteristics of natural willows?*

2. *Which management tactics can be implemented to increase the efficiency of the biomass harvesting and processing system?*

Three research plots were selected. The first plot is a willow ring that was harvested once (2013), the second plot was harvested twice (2006 and 2013), and the third plot was harvested three times (2006, 2009, 2013).

To answer the main research questions the sub-research questions below were proposed.

- *Is there a significant change in ratio of herbaceous matter in biobales after natural willow rings have been harvested multiple times in comparison to a first time harvested willow ring?*

- *What effect does harvesting of natural willow rings with an Anderson Biobaler have on the regeneration of shoots?*

- *What are: the ash content, burning characteristics and moisture content of biomass from harvested natural willow rings?*

- *Which management practices can be implemented to create a more efficient biomass harvesting- and handling system?*

Due to abnormal wet weather conditions the 2014 growing season was delayed; for this reason it was necessary to extend the research so that the required data could be collected. The extension created the opportunity to broaden the research drastically and explore in depth explanation for the data found in the first part of the research. The objectives during the extension of the research were to (1) determine the yield and mortality rate of native willow in harvested willow rings at the end of the growing season and (2) to determine if the wood-fired boiler is capable of handling shredded willow biomass derived from natural willow rings.
Additional research questions were set up:

- *What is the mortality rate of shoots for each willow species during the first growing season of harvested natural willow rings?*

- *What is the biomass yield for each willow species during the first growing season of harvested natural willow rings?*

- *What is the cost of producing wood chips from natural willow rings with the equipment used at the Agroforestry Development Centre, and how does this compare to the cost of fossil fuels?*

- *Is the KÖB Pyrot 300 successful in handling shredded willow biomass from natural willow rings?*

1.4 General approach

At the starting phase of this research a literature review was conducted on the ecology of willows native to the study area, on the Anderson Biobaler and on previously conducted willow ring studies. By using the information gathered during the literature review it was possible to determine which new data was required to answer the research questions. As a result of a late start of the growing season it was necessary to extend the research in to gather data on regeneration of willows after harvesting with the Anderson Biobaler had taken place. Additional research was required to determine why variation was present in herbaceous matter content of biobales. In addition the research was expanded to determine the mortality rate of shoots, yield of native willow, costs of willow biomass production and capability of the KÖB Pyrot 300 in handling shredded willow biomass.

1.5 Target audience

This report is commissioned by the Agriculture and Agri-Food Canada, Agroforestry Development Centre (ADC) in Indian Head Saskatchewan as a Bachelor thesis for the University of applied Sciences Van Hall Larenstein in Velp, the Netherlands.

It is the author's intent to inform the audience about the current status of research on willow ring harvesting as a source for renewable energy and to propose management tactics that increase the efficiency of the system.

This report is aimed at scientists who implement research in the field of Agroforestry, on the developments in biomass harvest around prairie wetlands. The practical details and down to earth advice can be used to inform landowners in the prairie porthole region.

1.6 Reading guide

The research methods that are applied throughout the research are stated in chapter two. The third chapter gives brief descriptions on *Prairie wetlands, willow harvest; plantation vs. willow rings, specifications of the Anderson Biobaler, specifications of the KÖB Pyrot 300, study area* and *description study plots.* The results of the research are presented in chapter four. The accuracy of the results is discussed in chapter five. Chapter six presents the conclusions that have been established with reference to the results of the research. The recommendations which have come forth out of this research are presented in chapter seven.

2 METHODS

Data was collected during this research through literature reviews, interviews with biomass experts at the ADC and by doing multiple field experiments. During the beginning of the research focus was dominantly put on doing literature reviews. During the course of the research the focus shifted to gathering data from field experiments and gathering data through interviews. Towards the end of the research focus was solely put on analyzing the collected data and doing additional literature reviews.

2.1 Literature review

Literature reviews were performed mostly during the beginning and end phase of the research. Data was collected through literature reviews on previous studies on willow biomass, biomass qualities, SRC-willows and the biomass harvesting system with the Anderson Biobaler. Scientific articles were found online and in the library at the ADC.

2.2 Interviews

During the research ample time was devoted to enquiries concerning the human understanding of all the different phases of deriving and processing biomass from natural willow rings. Those interviews were done on a frequent, mostly unplanned basis.

2.3 Fieldwork

Herbaceous matter content in biobales

To determine if there is a change in the ratio of herbaceous to woody matter in biobales, nine biobales (three from each site) have been un-rolled and sampled. The frequency in which the three willow rings were harvested differ from. Willow ring #1 (WR#1) has been harvested once (2013), willow ring #2 (WR#2) has been harvested twice (2007 & 2013), and willow ring #3 (WR#3) has been harvested three times (2007, 2009 & 2013).

The biobales were stored outside prior to sampling. For sampling the bio-bales were placed in a heated building. The frozen bio-bales required a 12 hour period to thaw which allowed uniform unrolling of the bale in a consistent layer. Prior to unrolling the weight of the entire biobale was recorded using a platform scale (1000kg full range; precision 0.2kg). After unrolling the biobale three sample segments were assigned for each bale; the centre of the first sample segment was set out at ¼ of the length of the unrolled bale, the second at ½ and the third segment at ¾. Each sample segment was one meter long and had the width of the biobale (circa 1.22m), the total sampled area per bale is 3.66m^2. The average surface are of the unrolled biobales was 22m^2 for WR#1, 12m^2 for WR#2 and 20m^2 for WR#3. Directly after unrolling the biobale a biomass sample was randomly collected over the length of the bale (with exclusion of the sample segments) to determine the moisture content of the bale at the moment of weighing.

In each sample segment the biomass was separated into herbaceous- and woody matter and stored in separate bins. Branches which were situated on the sample edges were carefully drawn to the side on which the largest portion of the branch was located. Willow shoots with large diameters were picked out by hand. The content of the bio-bale was sorted until woody biomass and herbaceous biomass were of equal dimension. From this point an industrial fan (Drieaz Ace Turbodryer (1/4hp, CFM 1881) was used to sort heavy biomass (dominantly branches and wood chips/shavings) from herbaceous matter. Test trials showed that an upward angle of 17.5 degrees resulted in the most accurate separation of woody- and herbaceous biomass. The centre of the fan was located at 34” from the ground. The highest setting on the fan was used to obtain the most accurate separation between woody- and herbaceous biomass. Small amounts of biomass were dropped from approximately 45cm above the centre of the fan ensuring a maximum dispersion of the biomass before it reached the floor.

Once the biomass of the sample segments was separated into woody- and herbaceous biomass portions, the weight of the two biomass types was measured using a platform scale (60kg full range; precision 5g). A sub-sample of the woody biomass weighed on a precision balance (8200g full range; precision 0.1g) and dried in a drying oven at a temperature of 65° C for a minimum of 96 hours until a constant weight was reached. After the drying process, the sample was weighed to determine the moisture content using the following formula.

$$Moisture\ Content\ (\%) = \frac{Wet\ Weight - Dry\ Weight}{Wet\ Weight} \times 100$$

For each herbaceous matter sample a random sub-sample (50g) was taken to analyse the exact biomass content and to determine the accuracy of the separation of herbaceous- and woody biomass. The content was divided into 4 classes; grasses, leaves, riparian vegetation and woody biomass. The total of each class per sample was weighed on a scientific weight scale, dried in a drying oven for a minimum of 48 hours at a temperature of 65° C and reweighed. The content of herbaceous matter was determined as a weight percentage of the total biobale.

Willow shoot regeneration

To determine the effect of harvesting of natural willow rings with an Anderson Biobaler on the regeneration of willows, study plots were established in three different willow rings from which biomass was harvested in the fall of 2013. For each willow ring a ten study plots were set out; five on the most northern side and five on the southern side of each willow ring. Each study plot was 1.0m^2, the plots were spaced 5m apart. The first data set was collected in the beginning of the growing season; in each study plot the number of stools and number of shoots per stool was recorded. Due to the early growth stage in which the willows remained it was impossible to distinguish different species.

In July, 2014 each willow plant found in a sample plots was identified according to genus and species by studying buds, bark, leaves and form.

For verification a second identification was completed during the collection of the second data set at the end of the growing season (October); At this time the number of stools, shoots per stool and dead shoots was recorded for each willow species in each plot.

Biomass yield and shoot mortality

The woody biomass re-growth in the study plots were manually harvested after the collection of the second data set. Exclusively new yielded woody biomass was collected; older woody biomass (primarily willow stools) present in the research plots were viewed as non-harvestable biomass. In each study plot the different willow species were collected and stored separately. Within each sample distinction was made between live and dead shoots. The samples were placed in a drying oven for a minimum of 72 hours at 65° C. Once the drying was completed the samples were weighed on a precision balance (8200g full range; precision 0.1g) to determine the yield DW. Live and dead shoots were weighed separately to determine the mortality rate by DW.

Ash content, burning characteristics and moisture content of native willow biomass

The effect of biomass harvests with an Anderson Biobaler in natural willow rings on the ash content and burning characteristics of natural willow was determined on the basis of newly collected data.

Biomass from WR#1, WR#2 and WR#3 was sampled to determine the moisture content; for each type a total of fifteen samples (approximate weight 2kg) was taken randomly spread out over the pile of shredded biomass. The samples were weighed on a precision balance (8200g full range; precision 0.1g) before they were placed in a drying oven for a minimum of 72 hours at 65° C. Once the drying was completed the samples were re-weighed. The moisture content of the sample was calculated on the wet weight basis. Each type of biomass was loaded in the storage silo located next to the biomass burner (KÖB Pyrot 300) for three separate burning studies. After the wood-fired boiler used all the fuel the entire system was cleaned to collect residues. The cylindrical burning chamber was cleaned with an industrial vacuum cleaner; the rest of the residues have been periodically removed by the ash-auger located underneath the wood-fired boiler. The ash-auger transports the residues to a metal container in which it is stored until the system is cleaned. The residues were weighed in the lab to determine the ash content for the willow biomass (on dry basis) from the different study sites. The results of these tests were compared to data which has been collected by scientists at the Agroforestry Development Centre during previous combustion sessions in the KÖB Pyrot 300 wood-fired boiler.

Capability of KÖB Pyrot 300 to handle shredded willow biomass
During the combustion process of the three types of willow biomass complications were recorded; by means of these complications it was determined if the Pyrot 300 boiler was capable of handling biomass derived from natural willow rings.

Management practices for a more efficient system
To propose a more efficient system I have reviewed literature, closely monitored the different phases of biomass processing, conducted interviews with biomass experts and equipment importers and analyzed data from the wood-fired boiler.

Cost of producing wood shreds from natural willow rings:
The cost of producing wood shreds from natural willow rings was determined by reviewing previously collected data by researchers of the ADC and by consulting information regarding costs of custom agricultural work. A comparison was made between the costs of heating the buildings, which are currently heated by the Pyrot 300 boiler, by biomass derived from willow rings and the costs of heating with fossil fuels.

2.4 Analysis

The analysis of the collected data was an important phase of this research. Multiple datasets have been analyzed; the intensity of the analysis was dependent on the significance and the extensiveness of the data sets. All the collected data was initially entered in Microsoft Excel 2010. The dataset concerning *content of herbaceous matter in biobales* was further analyzed with the statistical program Minitab.

3 BACKGROUND INFORMATION

3.1 Prairie wetlands

The thousands of shallow wetlands found on the northern glaciated plains of North America, and commonly referred to as the prairie pothole region (PPR), are the result of glacier activity during the Pleistocene glaciation. A landscape with many shallow depressions was left behind after the retreat of the glaciers approximately 12,000 years ago. These shallow depressions, known today as potholes or sloughs (fig 3.1), were caused by the creation of moraines, the abrasive force of moving glaciers, and the melting of large buried blocks of glacial ice (Sloan, 1972).

Figure 3.1: Prairie wetlands located near Indian Head, SK

Figure 3.2: The Prairie Pothole Region (PPR)

The PPR, located in the midcontinent of North America, covers approximately 715,000 km^2 and reaches from Iowa to Alberta (fig 3.2). The atmospheric environment of the PPR is largely influenced by the continental location and by the distance from the moderating influence of oceans. The climate of the PPR is considered to be continental (esask.uregina.ca). Winter temperatures can drop below -40° C while summer temperatures can exceed 40° C. Winds of 50 to 60 km hr^{-1} are common; during summer this contributes to drying of wetlands while it creates wind chills below -50° C during the winter.

The economic, hydrologic and ecologic systems of the prairie environment are strongly influenced by the presence of potholes. This is a result of their ability to act as chemical, nutrient and hydrologic retention areas, by providing important habitat for many flora and fauna species and by maintaining water table levels at a local and regional level (Hubbard, 1988).

Since the beginning of European settlement in North America the area of prairie wetland has drastically decreased. Studies by the Lands Directorate from 1986 showed that the area of prairie wetlands in Prairie Provinces in Canada has decreased by 71% and in the U.S.A by 75%. Wetlands loss has been a result of societal need for increased agricultural productivity and efficiency. It is estimated that more than 80% of the decrease in area of wetlands has been the results of transforming wetlands into agricultural land (Badiou, 2010).

Another change that occurred after the beginning of the European settlement was a decrease in the occurrence and intensity of prairie fires and a decrease in bison *(Bison bison)* populations that grazed on the prairies. Prairie fires and grazing, by bison or other ungulates, were of great importance for the prairie ecosystem (Stevens, 1993). These changes have also had a considerable effect on vegetation around potholes. Potholes in southern Saskatchewan are often surrounded by a "ring" of woody and herbaceous vegetation (fig 3.3). The dominant species within the woody vegetation is willow *(Salix spp.)*; therefore woody vegetation surrounding wetlands are commonly referred to as "willow rings". A study on willow rings identified four willow species growing in natural willow rings in southern Saskatchewan; beaked willow *(Salix bebbiana Sarg.)*, meadow willow *(Salix petiolaris Sm.)*, diamond willow *(Salix eriocephala Michx)* and pussy willow *(Salix discolor Muhl)* (Schroeder, 2009). Due to the decrease of natural disturbance factors, like prairie fires or grazing practices by ungulates, stand structure of willow rings has changed drastically in comparison to pre-European settlement (Coppedge, 1997). Willow rings are mostly over-mature and heavily degraded. Management practices are needed to restore variation in stand structure. A management practice currently applied involves harvesting natural willow rings with an Anderson Biobaler. The effect of harvesting willow rings with a biobaler resembles the effect of natural disturbing factors like prairie fire and intense grazing, trembling and rubbing practices by ungulates.

Figure 3.3: A pothole surrounded by a willow ring

3.2 Harvesting willows: plantations vs. willow rings

The growth characteristic of *Salix*, that permits the plants to regenerate vigorously after coppicing, has proven this genus to be ideal for short rotation woody biomass production. Internationally multiple species of fast growing willow are being used as Short Rotation Coppice (SRC) species on biomass plantations. In 2006 researchers at the Agro forestry Development Centre in Indian Head began developing a biomass harvesting system that exploits the growth characteristics of willows located in natural willow rings. This harvesting system makes use of non-cultivated willow species; these species are native to the region and have established naturally over time. Both woody biomass harvesting systems have derived their success using the willows capability to regenerate vigorously after coppicing. During harvest the stool and root system of the willow stays intact, while the remainder of the willow is removed as biomass. In the spring following the harvest re-sprouting takes place from the remaining plant parts of the willow (root system and stool).

Even though the fundamentals of SRC plantations and willow ring harvesting are largely similar, there are distinct differences between these two practices. The most significant differences are directly linked to the genesis of the practices. SRC willow plantations are created by humans specifically for the production of wood products. This practice is aimed at increasing productivity and efficiency to create a large financial output. In order to accomplish this, certain management tactics (use of cultivated species, herbicides, fertilizers etc.) are applied. SRC willow plantations are often located on land that is suitable for agricultural use; it is sometimes argued that willow plantations use land where potentially food production could take place.

The development of SRC plantations requires high initial costs; however, well-established SRC plantations have a life expectancy of around 25 years in which 6-7 harvests take place. Hybrid willow species are used with yields up to 12-15 DW tonnes per hectare (DEFRA, 2004). During the establishing phase of SRC plantations proper management is crucial; ground preparation before planting and weed control after planting is necessary to keep competition of other vegetation species to a minimum. After each harvest inputs of nutrients and herbicides are required to maintain a high productive crop.

Harvesting practices of SRC are primarily executed with modified self-propelled (SP) silage harvesters; these SP harvesters cut the woody stems and feed them through a chopper where they are then transformed into chips (fig 3.4). As a result of the high moisture content of fresh harvested willow, drying of biomass is essential in order to store biomass chips for a longer period of time. The high moisture content of has a negative effect on the dry calorific value of willow biomass (19.6 MJ kg^{-1} Dry Weight). The moisture content of fresh harvested willows is about 55-58% (Serup, 2005), at this moisture content the calorific value is approximately 7.5 MJ kg^{-1}. A decrease in moisture content of biomass leads to an increase in product- and calorific value. This also leads to a decrease in transportation costs due to the loss in weight and volume.

The long-term storage of willow chips has shown to be difficult. As a result of the high moisture content in willow biomass and the high content of bark and nutrients in young shoots a fast increase in temperature occurs in piled willow chips. Natural decomposition, caused by fungi and bacteria, starts virtually immediately once the un-dried willow chips are piled. During this process, in which wood breaks down to carbon dioxide and water, heat is released. This process results in a high loss of woody biomass (Serup, 2005). The process of decomposition is linked to the size of the chips. Research concluded that the decomposition is lower for larger chips due to the increased air movement between particles (Lehtikangas, 2000). Long-term storage of willow biomass without forced drying has the best results if the willow shoots are stored at uncut; however, this is a very expensive method of storage. Due to the high costs linked to forced drying and whole shoot storage, willow biomass chips are often directly transported to the end user.

According to Spinelli (2009) harvesting practices executed with SP harvesters have high hourly harvesting capacities; averaging 35t FW/h. The large financial investment required for purchasing SP harvesting equipment (> $500.000) and the necessity of having several additional tractors at site during harvest for direct transport of the chips are definite disadvantages to this system. The majority of harvesting practices are conducted during late fall and early winter, after willows have become dormant. Due to the low density of willow chips transportation costs are relatively high in comparison to other types of woody biomass such as round wood (Serup, 2005).

Figure 3.4: A self-propelled harvester

Figure 3.5: An Anderson Biobaler

Willow ring harvesting makes use of natural occurring willow stands; the aim of this practice is primarily to make use of what is present and to limit other disturbance factors, like land clearing. The goal of producing biomass can be complementary to other goals like mimicking natural disturbance to increase variation in the ecosystem or limiting vegetation encroachment on adjacent agricultural land.

Willow rings in the PPR are dominantly located around small wetlands. Some wetlands are located on terrains that are potentially suitable for growing valuable agricultural crops during dry years. However, the measures needed to make agricultural use possible are expensive and are not always economically feasible for the landowner. Harvesting natural willow rings has the potential to generate revenue from land that is currently deemed "unproductive". In contrast to the high development costs of SRC plantations willow rings occur naturally and are free of establishment and maintenance costs. Currently no management practices are applied to willow rings that favors an increase in woody biomass yield. Because no herbicides are applied herbaceous plants grow abundantly in non-harvested willow rings. The indirect application of nutrients occurs in a large number of willow rings due to water runoff from agricultural land, direct application of nutrients is currently not implemented. The woody vegetation present in the willow rings dominantly consists of native willow species, with an annual re-growth yield of approximately 3.5 ton ha^{-1} (Schroeder, 2009).

The mechanical harvesting of willow rings was experimentally evaluated in 2006 at Indian Head, Saskatchewan. For this the prototype biobaler developed by Savoie (2006) was used. The biobaler was based on an agricultural round baler; "the machine cuts, shreds and compacts the woody stems into a round bale" (Savoie, 2010). In 2009 the Anderson Biobaler has been taken in use for harvesting natural willow rings around wetlands (fig 3.5).
The willow ring harvesting system makes use of conventional agricultural equipment; which makes the system an easy transition for cattle ranchers and dairy farmers in the PPR since many of them are well equipped to handle round bales. The required financial investment ($120.000,-) for the Anderson Biobaler is relatively low. However, a tractor with a minimum capacity of 200HP is required to operate the Biobaler.

The hourly harvesting rate of the Anderson Biobaler in natural willow rings is 8-12 green ton/hour; however, this depends greatly on the characteristics of the willow ring. Harvesting takes place after agricultural crops surrounding the willow rings are harvested and the ground is frozen. Generally the harvesting season continues until snow accumulates in and around willow rings making access impossible. During harvest only one tractor and a biobaler are required. Tests have shown that the biobales are able to dry to a moisture content of around 20% in 10 months while being stored outside uncovered (personal communication Stefner, 2014). Temporary storage in dry areas surrounding the harvest site is possible and creates the opportunity to harvest multiple willow rings before transportation takes place. The costs to produce biobales from willow rings is calculated at $80,-/ton and the bales have an average density of 166.9kg/m^3 DW (personal communication Stefner, 2014).

Figure 3.6: The harvesting of WR #2 with the Anderson Biobaler

3.3 Biomass feedstock and heating system setup at the ADC

In the spring of 2012 a KÖB Pyrot 300 wood-fired boiler was installed and commissioned at the ADC in Indian Head. This fully automated combustion burner uses wood chips as fuel and is used to heat the greenhouse, laboratory and part of the administration building. The natural gas boilers were kept to handle peak load and function as the back-up heat supply.

The equipment used for the production, handling and processing of the biobales in Indian Head uses conventional bale- and silage handling equipment. An overview of the equipment used for this system at the ADC is shown on the right.

Present system at the ADC

- Tractor 200HP
- Anderson Biobaler
- 1-Ton truck
- Self-unloading bale trailer
- Tractor with grapple 85HP
- Hay shredder
- 5-Ton truck with box
- Silage wagon
- Silage blower
- 2500 Bushel storage silo
- KÖB Pyrot 300 wood-fired boiler

Harvesting

Biomass harvest of willow rings relies on the Anderson bio-baler. This equipment requires a tractor with a minimum PTO of 200HP and hydraulic remote controlled valves to operate the hydraulic features of the bio-baler.

Transport of bales

Transport of bales from the field to the storage site is executed with a 1-ton truck and bale trailer. Bales are loaded in the field by a small tractor with grapple. At the storage site the biobales are taken off the trailer by a small tractor equipped with a grapple after which they are stacked in a 3-2-1 pyramid.

Processing

Once the bio-bales have been dried to <20% moisture content, processing of biobales takes place in a conventional round bale processor. To obtain optimal wood chip uniformity, it was necessary to grind the biomass twice before loading it in the storage silo. A 2” screen in the bale processor is used to filter out the woodchips from the un-shredded biomass. The first grinding takes place at the biobales storage site. At the ADC a John Deere 7830 (200 HP) is used to propel the Haybuster Big Bite round bale processor. The bales are easily handled with a mid-sized tractor (85HP John Deere 5085m) equipped with a grapple. The wood chips land on a conveyor belt that deposits them in the box of a 5-ton truck. The capacity of the truck box is approximately 8 shredded bales. The biomass is transported to a pole shed where it can be stored until the biomass is required for the wood-fired boiler. Due to the low moisture content of the willow biomass the willow shreds can be stored without large risks of deterioration.

Feeding the storage silo

For this phase of the system the John Deere 7830, the Haybuster Big Bite H-1100 and the John Deere 5085m are used to grind the wood chips once more before transport to the wood-fired boiler took place. The wood chips are conveyed into the 5-ton truck that transports them to the location of the wood-fired boiler and the storage silo which is located right next to it.
A mid-sized tractor is required to propel a PTO driven silage blower and to hydraulically power a forage deck. The 5-ton truck is equipped with a hydraulic lift box that deposits the wood chips onto the forage deck. The forage deck is equipped with a walking floor that conveys the wood chips to a second conveyer that deposits them into the hopper of the PTO driven silage blower. The silage blower transports the wood chips to the top of the silo where it blows the wood chips in a downward trajectory into the silo. For

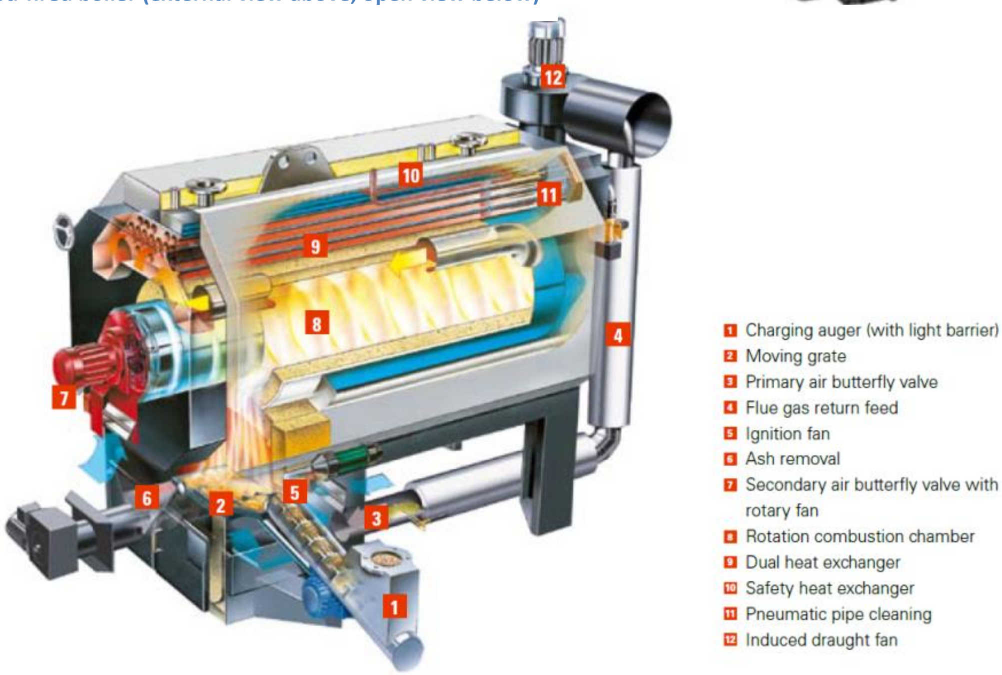
storage an ordinary 2500-bushel (80m^3) silo is used (fig 3.7); this silo is equipped with an elevated angled floor and rotating arms that transport the wood chips into a vertically placed auger.

Figure 3.7: The containerized wood-fired boiler plus storage silo at the ADC in Indian Head

3.4 Specification of KÖB Pyrot 300

The KÖB Pyrot 300, located at the Agroforestry Development Centre in Indian Head Saskatchewan is a high quality wood-fired boiler which was primarily designed for handling woodchips and pelletized biomass with moisture content <35%. The boiler was made in Austria by Viessmann Group and assembled and containerized by Fink Machines Inc. in Enderby, British Columbia. The Pyrot 300 is a fully automatic firing boiler equipped with a rotating combustion chamber; this enables optimal utilisation of the wood gasses while minimizing dust and other emissions (viessmann.co.uk).
Efficiency levels of up to 92% can be reached due to the combination of combustion technology and digital controls. The output rating of the Pyrot 300 is 270kW (1.000.000 BTU).

Figure 3.8: The wood-fired boiler (external view above, open view below)



3.5 Quality biomass from willow rings

Each type of biomass burner sets specific requirements on the quality of the fuel utilized in order to reach the highest potential efficiency. In general, uncontaminated biomass with low moisture- and ash content and a high uniformity in particle size is preferred. Biomass that meets these requirements burns with a higher efficiency, causes less down-time and results in lower maintenance costs of the boiler.
The KÖB Pyrot wood-fired boilers are specifically designed to handle fuels in the form of pelletized biomass and wood chips with moisture contents <35% (SparkEnergy, 2014).

A range of problems can be expected if biomass is used with low fuel qualities. In the table below the most common issues are described which result of low fuel qualities.

Table 3.9: Common problems resulting from low fuel qualities

High moisture content	Decreased calorific value – leads to increased need of biomass Decreased flue temperature – leads to increased condensation of acidic water in chimney and can cause chimney lining to corrode
High ash content	Increased fouling of wood-fired boiler – leads to decreased efficiency
Low uniformity	Increased risk of clogging of in-feed auger
Contaminated biomass (non - woody biomass, soil, rocks, etc.)	Increased ash- and slag deposits
High silica concentrations	Increased development of clinker and slag

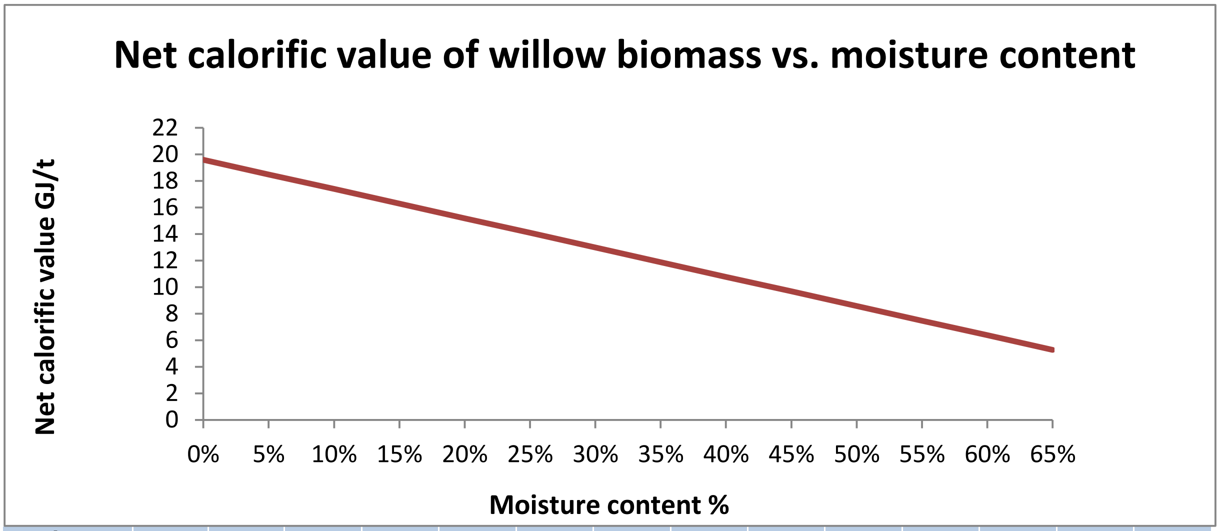
Calorific value of native willow species

The calorific value of most types of woody biomass is fairly constant; according to the Handbook of wood chemistry this is approximately 18MJ kg^{-1} dry weight (DW). The research of Schroeder et al (2009) studying biomass harvest from natural willow rings around prairie wetlands concluded that the calorific value of biomass from natural willow rings is “essentially equal to ‘conventional’ wood chips or purpose grown willows”. Combustions tests conducted at Natural Resources Canada CANMET Energy Technology Centre (CETC) in Ottawa. The tests concluded that the woody biomass in the biobales from natural willows has a calorific value of 19.6 MJ kg^{-1} DW (Schroeder, 2009).

Moisture content

As mentioned in table 3.9 the use of biomass with high moisture contents in a wood-fired boiler can lead to a number of problems. The calorific value of biomass decreases as a result of increased moisture content. The graph in figure 3.10 shows the relation between the net calorific value of willow biomass and the moisture content of this biomass. Increased biomass moisture content also results in decreased flue temperatures. This may cause evaporated acidic water to condense in the chimney which can lead to corrosion of the chimney lining, and increased maintenance overhead.

At harvest the moisture content of the willows can be as high as 55% (Kofman, 2012), this equals to a net calorific value of 7.5 GJ t^{-1}. The Pyrot 300 wood-fired boiler requires fuel with moisture contents below 35%, for this reason the biobales are dried for a minimum of 9 months. With the decrease in moisture content in the biomass the calorific value of the biomass increases.
The average moisture content of willow biomass burned in the wood-fired boiler at the ADC in Indian Head during the previous two years was 20% (personal communication Stefner, 2014). The table in figure 3.10 shows that the net calorific value of willow biomass harvested in natural willow rings is approximately 15.2 GJ t^{-1} at time of combustion.



Moisture content w.b. %	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%
Willow Net CV GJ/t	19.6	18.5	17.4	16.3	15.2	14.1	13.0	11.9	10.8	9.7	8.6	7.5	6.4	5.3

Figure 3.10: Graph and table of the loss of calorific value with increased moisture

Uniformity of biomass

The design of the in-feed auger system of the KÖB Pyrot 300 dictates the need for uniformly sized pelletized biomass and wood chips as fuel. The in-feed auger system requires fuel that flows easily. Both pelletized biomass and wood chips can be produced mechanically to meet the requirements of this wood-fired boiler. When using fuel that does not perform like the types of fuel the wood-fired boiler was designed for, the risk of clogging of the in-feed auger system will increase. To produce biomass feedstock from natural willow rings suitable for the KÖB Pyrot 300 bio-burner double shredding of chips was required to create biomass with acceptable uniformity.

Density

The density of shredded willow biomass (160 kg/m^3 DW) is relatively low in comparison to other types of biomass fuel like pine shreds (266.7 kg/m^3 DW.) and pelletized biomass (832.1kg/m^3 DW) (personal communication Stefner, 2014). The handbook of wood chemistry states that the low volume density of shredded willow chips required higher capacity storage facilities in comparison to types of woody biomass with higher volume densities.

Ash content

Ash is the non-combustible content of biomass and is generally expressed as a weight percentage of the total dry weight of fuel. Biomass with high ash content has low calorific values and causes increased emissions of dust and fouling of equipment during combustion; this leads to reduced efficiency of the wood-fired boiler (Rosendahl, 2013). The ash content of trees is different for each component of the tree. The ash content of willows was studied by Harder and Einspahr (1980); they found that the ash content of the sapwood is 0.9%, inner bark 13.1% and outer bark 11.5%. The total ash content of biomass derived from willow is highly dependent on the bark/sapwood ratio. Trees with a larger percentage of small diameter branches have therefore a higher bark/sapwood ratio; this results in higher ash content compared to trees with a smaller percentage of small diameter branches. The Wood Fuels Handbook states that SRC willow contains approximately 2% ash (weight % dry basis). Schroeder (2009) showed ash contents of approximately 1.65% for first time harvested native willow.

Silica concentrations

Silica (SiO_2) is an inorganic mineral that is, among others, present in biomass and soil. Combustion of biomass with high concentrations of silica leads to an increased development of clinker and slag in biomass burners (Melin, 2008) (fig 3.11). Silica is present in trace amounts in the wood of tree species in the temperate region (Pettersen, 1984); it is likely that the silica content of tree species in the Prairie zones is similar. In general the silica content of herbaceous biomass is higher than that of woody biomass; in addition to this herbaceous biomass has high alkali concentrations (K and Na). During combustion alkali compounds that are present in certain biomass "volatilize" and deposit within the biomass burner, which reduces the effectiveness of the heat transfer (Sims, 2002). In parts of the wood-fired boiler where silica sand has become available after combustion of biomass a reaction with alkalis will occur. During the alkali-silica reaction alkali silicate glass is formed; this process may lead to sintering in the boiler, decreased boiler availability and clog the auger that removes the ash from the combustion chamber (Steenari, 1997). Buildup of alkali silicate glass on the burner table can obstruct O_2 from penetrating the biomass from underneath. This leads to ineffective combustion of biomass, which on its turn leads to increased pollution of the heat exchanger by producing higher levels of dust or fly-ash (woodsure.co.uk).

Figure 3.11: Slag build up within the combustion chamber

The silica content of sapwood is lower than that of clean bark (Melin, 2008). Harder and Einspahr (1980) studied the bark of 24 hardwood species in the temperate zone and concluded that the average silica contents in clean bark of hardwood species is 0.11%; the average silica content in clean bark of softwood species is 0.05% (Ragland, 1991). Silica levels of non-cleaned bark are usually higher due to soil contaminated by wind during the growth period of the tree (Ragland, 1991). During harvesting- and processing practices additional contamination can occur; care will need to be taken during harvest and processing to keep this type of contamination to a minimum (Melin, 2008).

3.6 Study area and research plots

This study was conducted on three natural willow rings located near the Agroforestry Development Centre in Indian Head, Saskatchewan (50°30'N, 103°41' W, elevation 604.1m). The climate at Indian Head is considered to be continental (esask.uregina.ca). The precipitation recorded in 2014 varied greatly from the 1981-2010 normals (fig 3.12); during the months of April, June and August considerably higher than normal precipitation was recorded. The total precipitation recorded in 2014 was 562.5 mm; the normals for 1981-2010 showed an average precipitation of 432.2mm. Average daily temperatures were below average during February and March and were above average during April. Differences in precipitation and temperatures have an unknown impact on the growing characteristics of willow vegetation around prairie wetlands.

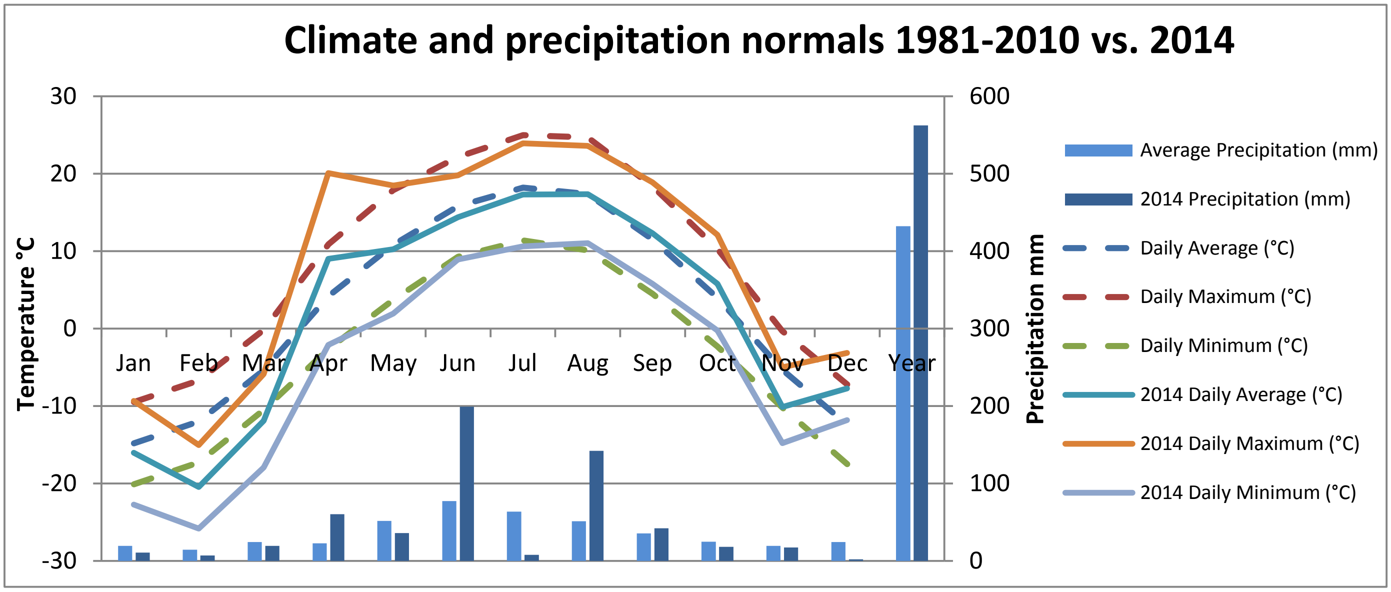


Figure 3.12: Climate and precipitation normal 1981-2010 compared to 2014

The frequency at which the three willow rings were harvested differed; WR #1 was harvested once (2013), WR #2 was harvested twice (2007 & 2013), and WR #3 was harvested three times (2007, 2009 & 2013) (table 3.13).

Table 3.13: Willow ring description

	WR #3	WR #2	WR #1
Number of harvests applied	3	2	1
Harvest year(s)	2007, 2009, 2013	2007, 2013	2013
Harvested area	1280m^2	690m^2	3609m^2
Topography	Flat	Large elevation	Small elevation
Average stool density/m2 (2008)	3.6	6.4	N/A
Dominant willow species 2007	*S. bebbiana*	*S. bebbiana* & *S. petiolaris*	N/A
Bales harvested 2013	15	7	25

WR #3 and WR #1 are located within a distance of approximately three miles from WR #2. All three willow rings were surrounded by agricultural crops (fig 3.14). For this reason biomass harvest was not possible before the agricultural crops were harvested. When biomass harvest took place in November 2013 all three willow rings contained no water and were accessible with harvesting equipment. Topography surrounding the three willow rings varied. WR #1 was located around a wetland with a small depressional elevation, WR #2 had a large depressional elevation and #3 had a nearly flat topography. WR #1 and WR #3 served as water retention reservoir for a large area, WR #2 served as water retention reservoir for a small area. More detailed pictures of the three willow rings are shown in figure 3.15 – 3.17.

Figure 3.14: Location willow rings

Figure 3.15: Willow ring #3

Figure 3.16: Willow ring #2

Figure 3.17: Willow ring #1

3.7 Previous research on willow rings at the ADC

Throughout the years several researches have been conducted at the ADC in Indian Head on willow ring harvesting. The results of the three most relevant researches are stated below.

In 2009 a study was published on "biomass harvest from natural willow rings around prairie wetlands" (Schroeder, 2009). In this study the production potential, fuel characteristics and effects of mechanical harvest of natural willow was determined. The most important results of the study were:

- The calorific value of natural willow was approximately 19.63 +- 0.26 MJ kg^{-1} DW; this is equal to what can be expected for other woody biomass.
- The ash content was determined at 1.65 +-0.09% by DW; this is slightly lower than for purpose grown willow.
- No significant difference was found between stools harvested with the biobaler or by hand pruning; all harvested stumps survived and had shoot regrowth.
- The number of shoots per stool differed for *Salix* species; *S. bebbiana* had significantly lower shoot regeneration than *S. petiolaris* while the other species were intermediate.
- Biomass regrowth was significantly affected by harvest method (P=0.05) and *Salix* species (P=0.01). Regrowth per stump ranged from 0.013 to 0.288 kg DW per stump.
- The biobaler managed to successfully cut and bale natural willow in a single operation.
- The majority of willows present in the study plots showed excellent regeneration.
- First year biomass production following harvest was 3.5 ton ha^{-1} DW.
- For some species cutting stumps to ground level results in reduced vigor and mortality.

A study on "Sustainable Biomass Production in Agroforestry Systems" (Schroeder, 2009) stated that:

- The Anderson Biobaler can efficiently harvest biomass from willow rings at a rate of 6.5tonnes/hour.
- The estimated cost of production of the biobales from willow rings was $50.00 per tonne DW.
- One oven dry ton (odt) of willow biomass has an energy equivalent of 400 liters of heating fuel.

In 2013 a study was conducted to the composition, stand structure and biomass estimates of willow rings on the Canadian prairies (Mirck and Schroeder, 2013). In this study 12 willow rings were examined, in each willow ring 4 plots were set out in which data was collected. The most important results of the study were:

- From the five native willow species *(S. petiolaris, S. discolor, S. bebbiana, S. eriocephala, and S. interior)* commonly found in willow rings, four showed a preference to the dryer (outside) part of the willow ring; only *S. petiolaris* preferred the moister inside part.
- The younger willow rings had high numbers of small diameter stems and a higher total number of stems per hectare than older rings.
- The portion of dead wood in willow rings increased significantly with the age of the willow ring.
- The most common native willow species in the 12 willow rings are *S. petiolaris* and *S. discolor*.
- There is a significant relationship present between the age of the willow ring and the presence of *S. petiolaris* (r^2=0.65); *S. petiolaris* is more present in young willow rings in comparison to old willow rings.
- Open water and dry willow rings were not significantly different for numbers of stems per hectare (p=0.11), total yield per hectare (p=0.13) and annual yield per hectare (p=0.50).

4. RESULTS

During the course of the research a variety of results were obtained. Several results gave new insights into the subject of the thesis, especially the results dealing with the quality of the biobales. Several results brought new questions that will require additional research.

4.1 Herbaceous matter content in biobales

In this research the objective was to determine the herbaceous content (HC) of willow bales from natural willow rings and to define management practices that will lead to a reduction of herbaceous matter content in willow bales.

In February 2014, a total of nine biobales from three different study areas were examined. For each study area three biobales were randomly selected to determine the herbaceous content. A summary of the results is shown in this chapter on the basis of a series of tables and graphs. The data was collected from biobales originating from three different willow rings; located approximately 4 miles from each other. Variation between willow rings consists of e.g. topography, shape, water table and dominant woody- and herbaceous vegetation. The comparison between willow rings is made to find out whether a variation of herbaceous matter is present.

During the examination of the biobales various types of herbaceous matter were distinguished (table 4.1). The first type ("grass") consists of various grass species, the second type ("leaves") consists of leaves of unspecified plant species and the last type ("riparian") consists of riparian vegetation species (dominantly cattail (Typhus spp.)).

Table 4.1: Average herbaceous content in biobales by dry weight percentage

Study area	Avg. grass	Avg. leaves	Avg. riparian	Avg. Total
WR #1	0.82 %	3.76 %	0.00 %	4.78 %
WR #2	0.72 %	0.22 %	1.40 %	2.35 %
WR #3	8.52 %	2.31 %	0.00 %	10.82 %

A statistical analysis (treatment comparison) was made to determine if the herbaceous contents were significantly different ($p>0.05$). One sample in willow ring #1 was found to be not representative; for this reason the decision was made to exclude this sample in the statistical analysis. The data was first transformed to natural log; which increased the accuracy of the data analysis.

The data for each sample was used to determine if the variation of herbaceous matter types within each willow ring were significantly different from the variation of data found in the other willow rings. A total of four graphs with box-plots have been created to show the variances of each type of herbaceous matter found in the willow bales (fig 4.3). Above each box-plot a letter (X, Y or X) is shown; box-plots in the same graph with the same letter were found to be not significantly different ($p>0.05$). The standard error is shown in the whiskers of the box-plots.

Grass

The treatment comparison found the grass content in biobales from WR #1 and WR#2 to be not significantly different ($p=0.6164$); however, WR #1 and WR#2 are both significantly different from WR #3 ($p=0.0027$ and $p=0.0004$ respectively) (fig 4.3A).

Data collected post-harvest on grass regeneration in the study plots showed distinct differences between the three willow rings. At harvesting the ground cover of herbaceous plant species was estimated in each study plot; ground cover averaged 20% in WR #1, 20% in WR #2 and 60% in WR#3. The results of the ground-cover estimates match with the results of the herbaceous matter content in biobales. WR #2 was found to have the lowest herbaceous content (HC) in biobales and the lowest ground cover of herbaceous species. WR #3 had the highest HC in biobales and the highest ground cover after the first growing season.

Variances in presence of herbaceous species in the three willow rings are likely due to several factors. The variance in topography is expected to have a major impact on the local growing conditions; this will result in growing conditions that favor different vegetation species. A description of the topography of the willow rings is given in chapter 3.6. The stand structure of willow species in willow rings is also expected to have a great effect on the presence of herbaceous vegetation. More herbaceous vegetation can likely be found in willow rings with less dense stand structures, since more sunlight will reach the ground. WR #1 concerns an old willow ring that had never been harvested; willow vegetation is expected to have outcompeted other types of non-woody vegetation. WR #2 has been harvested twice (2007 &2013); it is likely that the six-year period between harvests has given willow vegetation the chance to outcompete other non-woody vegetation. WR #3 had been harvested three times (2007, 2009, and 2013). It is assumed that the non-woody biomass was not yet supressed by canopy cover provided by the willow vegetation. In the four-year period between the second and the third harvest the willow vegetation will probably have started to show signs of suppressing the non-woody vegetation. However, additional time was probably required to reduce the density of herbaceous vegetation. Additional research is required to substantiate this hypothesis.

Leaves

The leaf content of WR #1 and WR #3 is significantly different from WR #2 (p=0.0000 and p=0.0003 respectively). There were no significant differences found between WR #1 and WR#3 (p=0.3038) (fig 4.3B). Due to the particle size of the leaves found in the samples it was impossible to distinguish the willow species these leaves originated from.

Additional data was collected to determine the origin of the leaves content. This was obtained by determining the percentage of leaves left on shoots at time of harvest in 2014 (fig 4.2). The average content of leaves on shoots per willow ring was estimated individually; WR #1 was estimated at 7.8%, WR#2 at 4.9% and WR#3 at 3.2%. Although no data was collected, a general observation was that a larger amount of leaves were present on dead- than on live shoots.

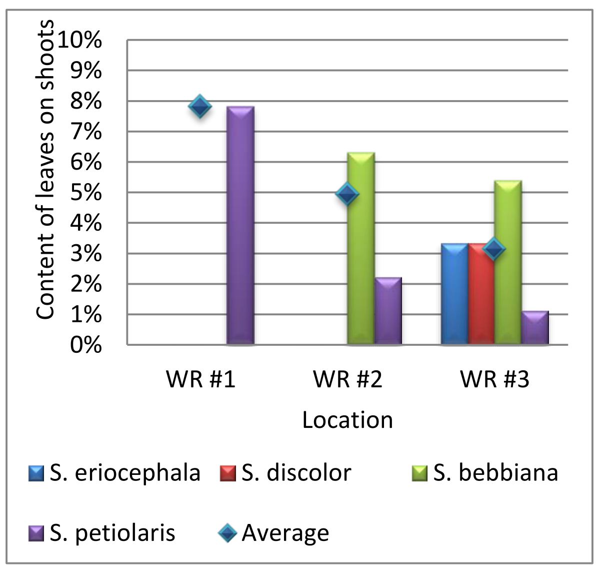


Figure 4.2: Content of leaves on shoots

The data collected on the percentage of leaves on shoots does not explain the results found in the herbaceous matter sampling. A study by Schroeder (unpublished data) concluded that the DW of certain willows consists up to 18% of leaves. Even though no data is available on the partitioning of leaves and stems for willow species native to the PPR the assumption can be made that similar percentages can be expected. The data collected on the content of leaves on shoots showed much lower numbers than required to explain the content of leaves found in willow bales. It was therefore concluded that the leaves found in the willow bales were not connected to the willow shoots at time of harvest; the biobaler has likely picked up leaf litter from the ground during harvest. The absence of leaves in the samples of WR #2 is likely a result of leaf litter being removed by strong winds. The ground cover of WR #3 was much higher than that of WR#2; this could have resulted in less removal of leaf litter in WR #3 in comparison to WR#2. The high leaves content in WR #1 in comparison to WR #2 is possibly a result of the difference in shape and orientation of the willow ring (fig 3.14 p.28).

Riparian

No biomass was found in samples from WR #1 and WR #3 that could be classified as riparian vegetation (fig 4.3C). For this reason WR #1 and WR #3 were found to be not significantly different from each other (p=1.0000), but they were both found to be significantly different from WR #2 (p=0.0059 and p=0.0059 respectively). In WR #1 and WR #3 cattail *(Typha spp.)* vegetation was present post-harvest at low density. However, cattail vegetation was present in high densities in WR #2. According to pictures from the pre-harvest situation, cattails were located throughout the entire willow ring. At certain locations cattails were the dominant vegetation.

Total herbaceous matter content

WR #1 and WR #2 contained significantly less herbaceous biomass than WR #3 (p=0.0008 and p=0.0001 respectively) (fig 4.3D). Biobales from WR #1 contained significantly more herbaceous biomass than biobales from WR #2 (p=0.039). Herbaceous matter contents in samples varied between 0.4% and 17.6% DW. The average herbaceous content varied from 2.38% to 10.74% DW. It is expected that in willow ring harvesting systems similar results will be found. Local growing conditions and applied management methods in willow rings cause variation in herbaceous matter content. A high content of herbaceous matter is known to cause difficulties during combustion (table 3.9, p. 24). If this appears to be a problem for biobales from natural willow rings, special management methods might be required.

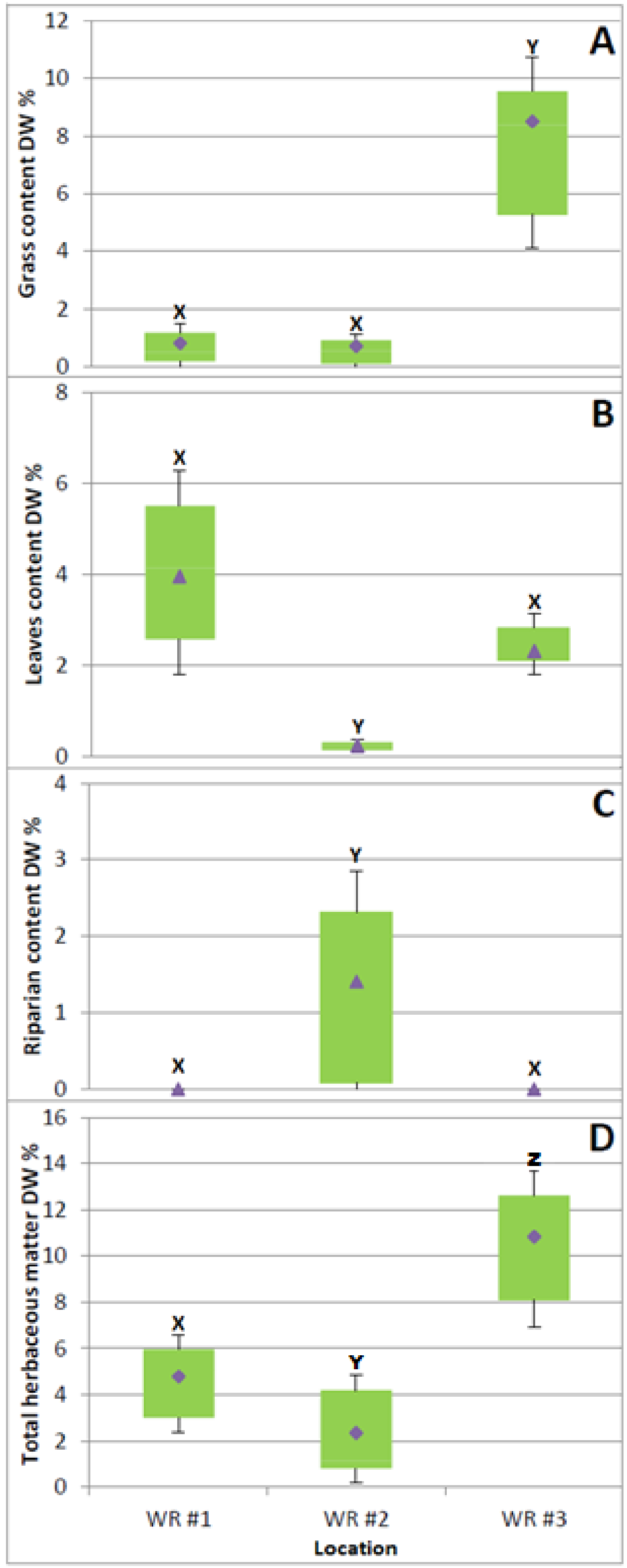


Figure 4.3 A: Grass content in biobales, B: Leaves content in biobales, C: Riparian vegetation content in biobales, D: Total herbaceous matter in biobales. The whiskers of the box-plots show the standard error.

4.2 Effect of harvesting on willow regeneration

In May 2014 data was collected on the regeneration of willow shoots during the first growing season after harvest. All willow shoots located within the 30 study plots were counted. Due to the early growth stage it was not possible to distinguish willow species. It was also not possible to accurately determine the number of stools located in the study plots due to the high level of shredded stools, which is likely caused by the method of harvesting. It was only possible to determine the density of shoots per m^2 in each study plot. Therefore the average number of shoots per stool could not be calculated, posing a difficulty comparing those early spring results with the autumn results.

Research from Mirck (2013) found that "open water and dry willow rings were not significantly different for numbers of stems per hectare (p=0.11), total yield per hectare (p=0.13) and annual yield per hectare (p=0.50)". For this reason the assumption is made that the harvest intensity is the only variances present within the willow rings at the time of data collection in May, that has an influence on the number of shoots per stool.

After analyzing the data set it was concluded that there is a slight increase in the number of shoots regenerated per m^2 by an increase of applied harvest (fig 4.4). However, this variation was found to be not significant. Shoot regeneration was lower, but not significantly, in WR#1 (73.6/m^2) than in WR #2 (91.8/m^2) and WR #3 (101.5/m^2) (p=0.29 and p=0.07 respectively). Shoot regeneration in WR #2 was lower, but not significantly, than in WR #3 (p=0.37).

In November 2014 data was collected again on willow regeneration. All willow shoots that were located in the 30 study plots (set out in May 2014) were harvested and taken to the lab for further analysis. The objective was to determine the effect of repeated harvesting of natural willow rings on the regeneration and yield of native willows.

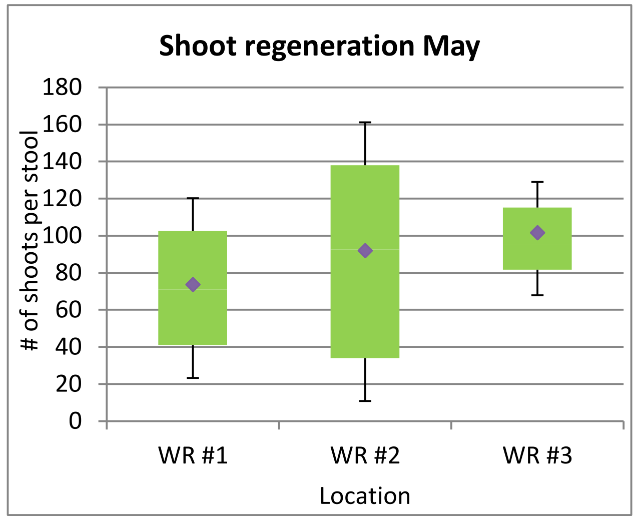


Figure 4.4: Shoots per stool May

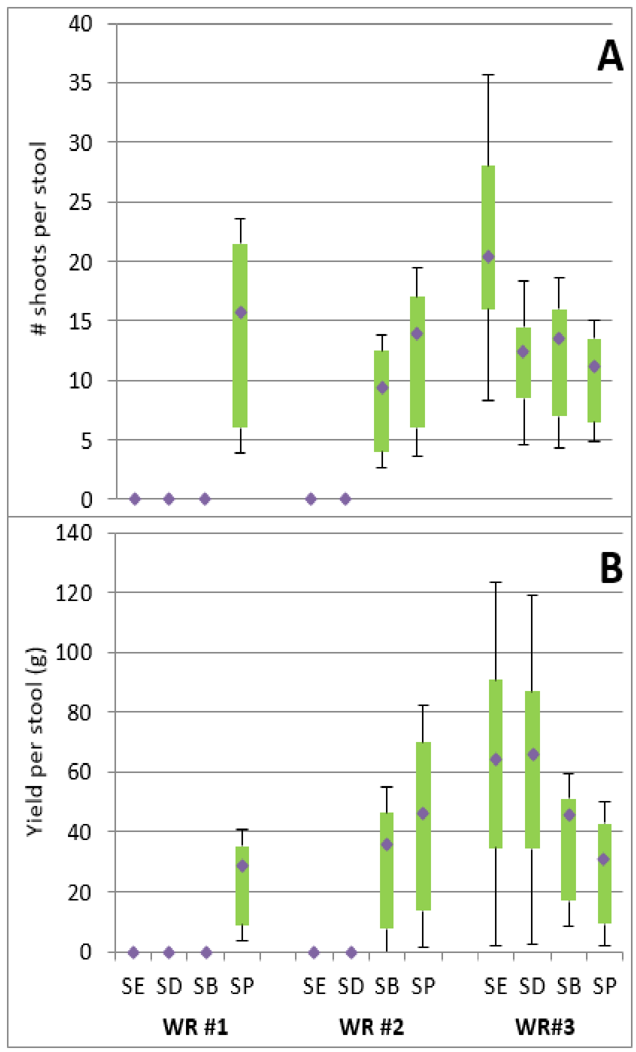


Figure 4.5 A: Shoots per stool November. B: Yield per stool (g) The whiskers of the box-plots show the standard error.

In the three willow rings a total of four different willow species were found: *Salix discolor*, *Salix eriocephala*, *Salix bebbiana* and *Salix petiolaris*. *S. discolor* and *S. eriocephala* were only found in research plots at WR #3, *S. bebbiana* was found in research plots at WR #2 and WR#3. *S. petiolaris* was the only willow species found in all three willow rings; for this reason focus will be put on this species for comparing results between the three willow rings. Three study plots contained no willow vegetation; all these plots were located in WR#2. Due to the small sample size of *S. eriocephala* and *S. discolor* it was not possible to analyze the collected data and draw conclusions concerning these species.

Schroeder (2009) showed variation between species in number of shoots per stool regenerated after harvesting with the prototype biobaler. It was therefore expected that the effect of repeated harvesting on the number of shoots regenerated per stool would vary by species.

Variation in number of shoots per stool was found within species between the willow rings. *S. petiolaris* showed a slight decrease in number of shoots per stool with an increase in number of harvests. However, variation was found to be not significant. *S. bebbiana* showed an opposite trend with a higher number of shoots per stool in WR #3 than in WR#2; however, it needs to be noted that this species was absent in WR#1 (fig 4.5A).

Growing conditions in all willow rings were severely affected by the abnormal precipitation recorded between June and August 2014 (fig 3.12, p.27). For this reason it was not possible to assume that the yield of willows was only affected by the number of harvests applied. Therefore the assumption was made that the yield per stool was primarily affected by inundation period.

WR #1 became fully inundated in June and remained this way throughout the entire year; the research plots contained more than six inches of water in the month of July. WR #2 became fully inundated in June but showed gradual decline of the water level as the season progressed. With the research plots not containing any surface water by the month of September. WR #3 became partially inundated in June. The research plots were fully inundated at this moment; however, the plots did not contain any surface water in the month of August. The presence of *S. eriocephala* in WR #3 is remarkable due to the fact that this species prefers wet conditions (Mirck, 2013).

As mentioned in chapter 3.7 *S. petiolaris* has a preference for wet growing conditions and *S. bebbiana* prefers drier conditions. Similar results were found for the yield per stool in this research. A non-significant variance in yield per stool was found between the three willow rings; *S. petiolaris* showed a higher yield in WR #2 than in WR#1 (p=0.18) and WR#3 (p=0.27) (fig 4.5B). Season-long inundation in WR #1 caused a high mortality of shoots (chapter 4.3), which resulted in a very low yield per stool compared to this species in WR#2 and WR#3. The inundation in WR #3 ended early in the growing season; which negatively influenced the growth of *S. petiolaris*. The higher yield of *S. bebbiana* in WR #3 compared to WR#2 can be explained by its preference for dry conditions.

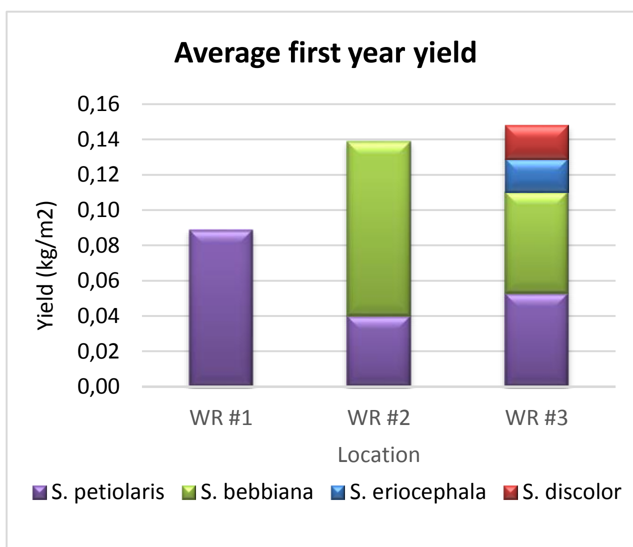


Figure 4.6: Average yields per willow ring classified by species

The results on yields were compared to results from a research conducted by Schroeder (2009); the yield of each species found in the 2014 research was lower than those found in 2007. This difference is probably a result of the abnormal wet weather conditions in 2014 compared to 2007; however, additional research is required to determine if this is correct.

The average yield for each willow ring is shown in figure 4.6; distinction was made between the four willow species found. The average re-growth annual biomass yield ranged from 0.89 oven dry ton (odt) ha^{-1} y^{-1} to 1.48 odt ha^{-1} y^{-1}. Yields found in WR #3 were approximately 34 % higher compared to those in WR#1; this is likely caused by the high mortality of shoots in WR#1.

4.3 Mortality rate of willow shoots

The 2014 growing season was exceptionally wet; during the month April, June and August the precipitation was double of its normal (fig 3.12, p. 27). Inundation was so severe during the willow ring harvesting season that no harvest activities could have taken place in WR #1 and only approximately 10% of WR #2 could have been harvested. WR #3 was fully accessible for harvesting activities early in the willow ring harvesting season (end of September). The objective was to determine the mortality rate and possible mortality causes of native willow shoots.

In the 30 study plots, a total of 1360 shoots were collected from 105 stools. The results of the data analysis on willow regeneration showed high mortality rates in all three willow rings (fig 4.7A). The mortality rates are based on absolute numbers of live and dead shoots harvested in the study plots in November 2014. The mortality rate of shoots per stool for *S. petiolaris* was 70.5% in WR #1, 41.6% in WR #2 and 31.7% in WR #3.
To determine at what growth stage the majority of the shoots per willow species died the Dry Weight (DW) was determined of all live and dead shoots from each willow stool. The mortality rate by DW was then calculated (fig 4.7B).

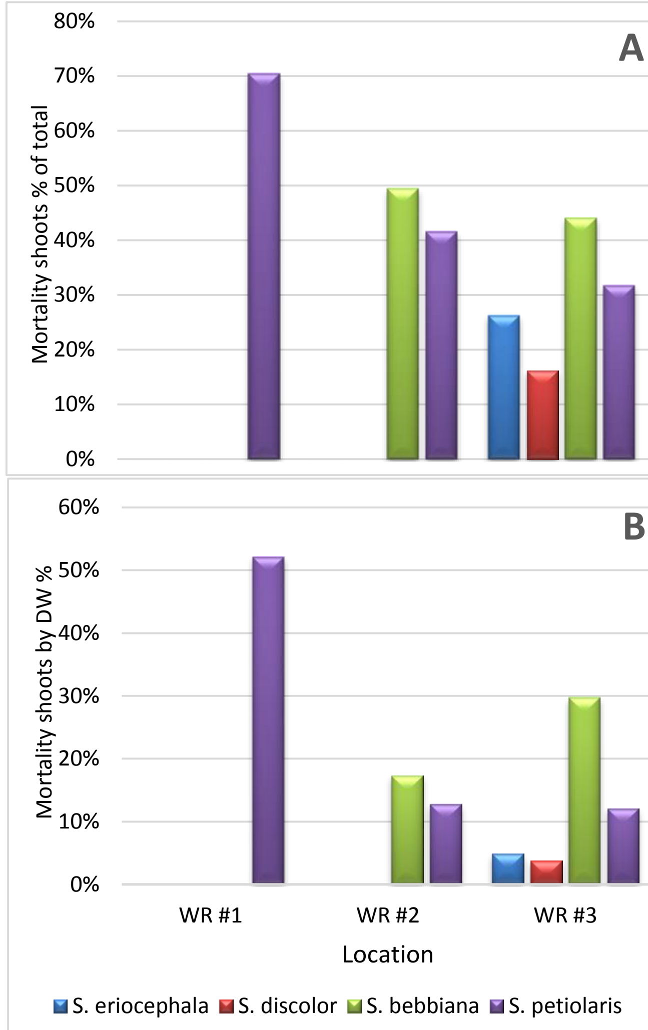


Figure 4.7 A: Mortality by # of shoots B: Mortality by DW

S. petiolaris in WR #1 had a shoot mortality rate of 70.5%; however, the mortality rate as a percentage of the total DW was 52.1%. In WR #2 *S. bebbiana* and *S. petiolaris* showed a different trend with 49.4% and 41.6% for mortality rate of shoots and 17.3% and 12.7% for mortality rate by DW. WR #3 shows similar trends as WR #2; three out of four willow species found had a mortality rate by DW that was much smaller than the mortality rate of shoots. Only *S. bebbiana* showed a mortality rate of shoots that was similar to the mortality by DW.

To determine the cause and moment of mortality for willow shoots the average DW for live- and dead shoots was calculated (table 4.8). The average DW of each dead shoot ranges between 14.49% and 53.62% of the DW of live shoots of that species in that particular willow ring.

The differences in mortality in shoots and by DW show that mortality did not take place at the end of the growing season, in that case the weight of live and dead shoots would have been equal. By means of these results it can be concluded that mortality of shoots has predominantly taken place early in the growing season and was likely caused by long-time inundation.

Table 4.8: mortality rate by DW

	S. p #1	*S. b* #2	*S. p* #2	*S. e* #3	*S. d* #3	*S. b* #3	*S. p* #3
DW / shoot live (g)	2.85	6.38	4.78	3.97	5.95	4.08	3.37
DW / shoot dead (g)	1.30	1.37	0.98	0.58	1.22	2.19	1.00
Mortality rate / DW (%)	45.52	21.47	20.50	14.49	20.44	53.62	29.72

The overall mortality has been calculated with the dataset collected in May and the dataset collected in November. The overall shoot mortality of WR #1 was calculated at 92.01%, WR #2 at 81.52% and WR #3 at 69.06%. No reference data is available concerning shoot mortality of willow species during the first growing season. For this reason it is not possible to determine the significance of the data on shoot mortality found in this research.

Although no data was collected, a general observation was that previously harvested willow rings in which high mortality occurred during the first growing season as a result of extended inundation were re-colonized by native willow within a few years (personal communication with Stefner, 2014).

Figure 4.9: Inundation in willow ring

4.4 Characteristics of biomass from willow rings

Biomass derived from the three willow rings in November 2013 was shredded in September 2014 to fuel for the ADC bio-burner. The objective was to determine the characteristics of the biomass derived from the three willow rings and to determine if the KÖB Pyrot bio-burner can successfully handle the biomass. The average moisture contents of the biobales for each study area were calculated and compared to results from March 2014. All bales were dried outside and uncovered.

No sign of drying was found in biobales from WR #1, and only limited drying in biobales from WR #3. Biobales from WR #2 showed a significant change in moisture content between March and September; their moisture content dropped from approximately 34% in March to approximately 14% in September (table 4.10). The speed of drying is probably greatly influenced by the content and type of herbaceous matter in combination with the average shoot diameter and density of the biobale. Additional research is required to back up these hypothesises.

Table 4.10: Moisture content biobales

Study area	H.C.	M.C. March	M.C. Sept.
WR #1	4.78%	34.13%	34.81%
WR #2	2.35%	33.97%	13.79%
WR #3	10.82%	38.18%	29.62%

Problems arose after bales from WR #3 were shredded: heat generation started directly after the shredded biomass was piled. To prevent spontaneous combustion the biomass was spread-out in a covered location; after an additional drying time of 14 days the biomass was loaded into the storage silo. The biomass had an ash content of 6.14%; this is more than triple of what is found for other types of biomass, and the highest ash content recorded so far at the ADC. The high ash content was likely the result of high contents herbaceous matter which contains high silica concentrations.

The biobales from WR #2 had low moisture content at time of shredding. No problems were noticed during processing and storage of the biomass. However, clogging occurred in the transition of the square- to the round auger tube. It is expected that continuous clogging was the result of the extremely low density of the willow shreds (table 4.11). Combustion did not take place as a result of the continuous clogging; for this reason no data was derived on the ash content of the biomass. The current bio-burner was found to be incapable of handling biomass with these qualities. Therefore alterations to the design of the wood-fired boiler are required to make combustion of fuel with these characteristics this possible in the future.

Biobales from WR #1 contained a moisture content of 34.8% at the beginning of the heating season. Directly after shredding took place heat started to generate in the piled willow shreds. Due to the extremely high moisture content the decision was made to not load this biomass into the storage silo. In November biobales from WR #1 were shredded; due to the low outside temperature (-20^{o}C) no internal heating occurred. No problems were found during combustion; the ash content was 2.98% with little glass build-up in the combustion chamber.

Table 4.11: Moisture content, bulk density and ash content of biomass

Species and Source	Wood Pellets	Pine	WR #1	WR #2	WR #3
Moisture content (%)	8.0	27.8	34.8	13.8	29.6
Bulk Density (kg/m3)	832.1	266.7	274.8	159.1	N/A
Ash content (%)	0.36	0.93	2.98	N/A	6.14

4.5 Changes to the system

The objective was to increase the efficiency of the biomass harvesting- and handling system. The system at the ADC has been in use since the beginning of 2012. During the course of its two and a half years of being commissioned a number of setbacks were observed.

The main bottleneck of the system is the present way the shredded biomass is stored. The current biomass storage silo located next to the bio-burner has shown to be unsuitable for shredded willow biomass applications. As a result of the low density of this type of biomass the silo can only hold biomass for approximately 10 days during peak demand when the bio-burner is operating at full capacity. In addition the way of loading the silo with biomass has been found to be very inefficient and time consuming.

In order to create a more efficient system, that is better manageable for future users, some propositions are made to increase the efficiency of the entire biomass system.

To increase the cost efficiency of the system it is necessary to reduce the distance of transport, the number of handling times and the amount of equipment used. Much room for improvement was found in the processing- and silo-loading phase. No changes to the harvesting activities and the transportation of biobales from the harvesting- to the storage location are required. In the latter two activities experienced equipment operators will lead to a reduction in handling time and therefore to cost reductions.

The system could be greatly improved if a large topless storage silo is placed in the biomass storage pole shed (fig 4.12). Long-time storage of biobales should be within a small distance of the pole shed - this will minimize handling time for biobales. To decrease the possibility of contamination by soil, biobales need to be stored on a dry and clean base. The use of concrete pads for storage is ideal, but very costly. Another, possible more cost-efficient way of storage consists of spreading out a thick layer of flax straw on which the bales are placed. Flax straw decomposes very slowly and is often seen as a waste product in agricultural operations. Bio-degradable twine can be used if no additional handling of bales, besides loading them into the shredder, is required after the drying process is completed. Biodegradable twine reduces the plastic-load for the wood-fired boiler.

With a small tractor and a grapple biobales can be stacked for storage in a 3-2-1 pyramid. After stacking the bales can be covered with a "bio-blanket" for improved drying.

An open-top silo makes loading biomass with a single tractor with a grapple possible. The auger setup supplied by Fink will stay mostly unchanged; however, the length of the auger will need to be adjusted depending on the size of storage silo chosen.

Biomass storage will take place in a large pole shed with a concrete floor to prevent contamination of the biomass by soil or water. Preferably the pole shed stores the amount of biomass that can be shredded during an 8-hour work day. Data from the ADC shows that the Shredder can shred approximately 1 bale per minute; this is approximately 15 tons DW/hour. Biomass needs to be shredded twice to get the required uniformity. In eight hours a total of 60 tons DW (240 biobales) can be

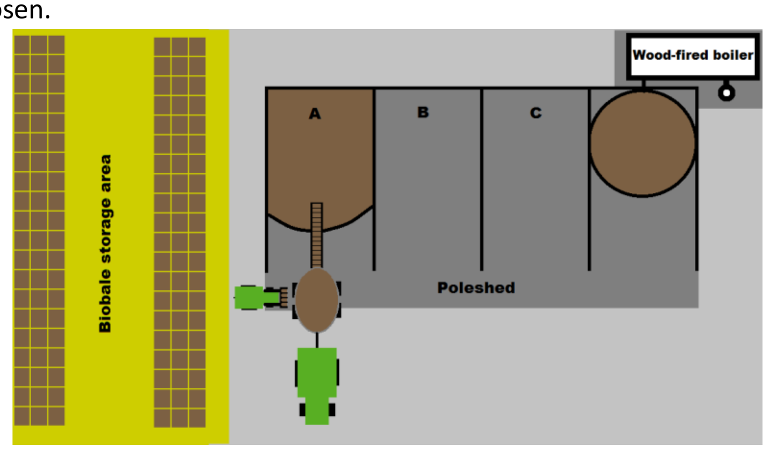


Figure 4.12: Proposed design for biomass handling facility

shredded. To store this amount of biomass a pole shed with a storage volume of approximately 500m^3 is required. A 300kW wood-fired boiler uses approximately 300 tons of biomass per heating season; this is equal to circa 1200 biobales. Shredding will need to take place several times during the heating season.

The minimal working clearance of the building depends on the dimensions of the tractor used to load the open-top silo with shredded biomass. The minimum required height is 11 feet.
Once area A (fig 4.12) is filled with one time shredded biomass the tractor and shredder will need to be repositioned in front of one of the other bays. The small tractor with grapple which first loaded the shredder with biobales will now be used to load the shredder with one time shredded biomass.

Figure 4.13: Biomass shreds from WR #2 (left) and WR # 3 (right)

4.6 Changes to the KÖB Pyrot 300

In chapter 4.4 it was concluded that the wood-fired boiler located at the ADC in Indian Head was not capable of handling all types of shredded biomass derived from natural willow rings. It was therefore the objective to determine what changes are required to the wood-fired boiler to improve its capability of handling shredded willow biomass.

The largest obstructions while handling shredded biomass were found in the in-feed auger system. The transition between the rectangular auger box and the auger pipe is rather abrupt. Thus biomass frequently builds up in the top left corner of the auger box. In addition the stringiness of the biomass causes it to get caught in between the in-feed auger and the auger pipe. The biomass pushes the auger to one side after which a ½" spacing is created on the opposite side. This spacing is an additional cause for biomass clogging on the transition between the auger box and the auger pipe.

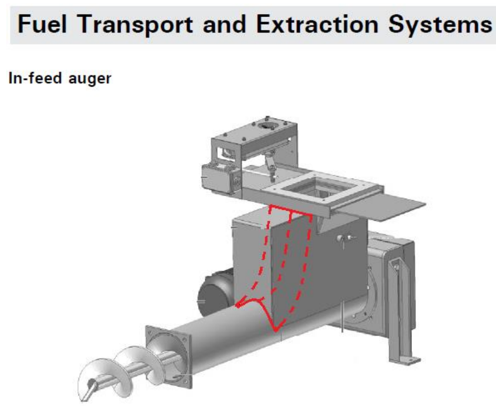


Figure 4.14: In-feed auger system KÖB Pyrot 300

To prevent biomass from building up in the auger box a metal plate needs to be installed (fig 4.14). This plate will create a smoother transition between the auger box and the auger pipe. Installing an auger that fits tightly in the auger pipe can possibly eliminate biomass build-up between the in-feed auger and the auger pipe. Polarity switches need to be installed on the in-feed augers in order to be able to reverse their turning direction. This will allow for easy removal of a possible clogging.

The proposed changes to the Pyrot 300kW bio-burner have a combined cost of $2030,- (table 4.15). After these modifications the bio-burner will probably be more capable of handling shredded willow biomass as primary fuel.

Table 4.15: Estimated costs KÖB Pyrot 300 modifications

Description activity	Expected costs
Installation of plate in rectangular auger box	$400,-
Replacement of auger	$1150,-
Installation of polarity switch on in-feed auger	$240,-
Installation of polarity switch on ash auger	$240,-

4.7 Costs of willow biomass production

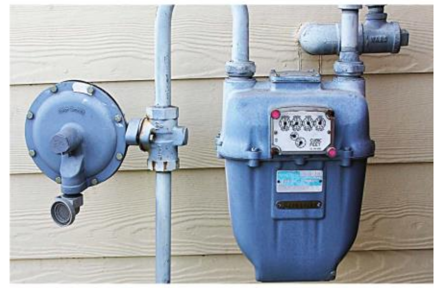
Cost calculations were made on the basis of data from a survey on custom rates by the Ministry of Agriculture and Rural Development Alberta. No custom rates were available for the baling process; for this reason the cost-calculation of Anderson Group was used.
A more detailed overview of costs of each handling phase is shown in appendix 1.

The average heat requirement of the buildings currently heated by the wood-fired boiler at the ADC is 1800GJ per year. To produce this heat solely by biomass derived from natural willow rings a total of 120 tons, with a moisture content of 20%, is required. The costs of harvesting, transportation and processing was calculated at $98.03 per ton; this brings the total to approximately $11.600,- (fig 4.16). When the costs of producing biomass from native willow rings is compared to the costs of other types of energy it will be noted that only natural gas is currently less expensive. Biomass shows great cost advantages over fuels like propane, heating oil and electricity. These calculations are solely based on the cost of fuel; differences in the costs of installations to generate heat with these types of fuel are not taken into this calculation.

Historical data on fuel prices show great fluctuations: the cost of natural gas is currently approximately 52% lower than in 2006 (saskenergy.com). The costs of biomass are less likely to fluctuate.

Calculations have shown that when the handling of biobales is not done by a contractor the total costs decrease to $79.10 per ton. The costs of meeting the current demand of 1800 GJ at this rate is approximately $9.360,-. Since a small tractor with grapple is needed to load the open-top storage silo with biomass shreds it would be financially beneficial to use this piece of equipment throughout the entire handling process.

$ 9.360,- to $ 11.600,-



$ 10.650,-

$ 49.500,-

$ 55.900,-

$ 65.000,-

Figure 4.16: Cost of biomass fuel in comparison to other types of fuel (calculated at 1800 GJ)

4.8 Proposed management practices

To increase the efficiency of the system a number of measurements are proposed.

Changes to harvesting

The efficiency of the system can be greatly increased by improving the quality of the biobales harvested in the willow rings. As mentioned in chapter 4.4 it is likely that the drying time of biobales increases drastically when they contain a large percentage of herbaceous matter. Increased drying time causes the need for more storage space, which leads to larger distances from storage to processing. This results in lower productivity and increased fuel consumption. For this reason it is important to decrease the content of herbaceous matter in biobales. This is easiest achieved by changing management tactics on harvesting. A decrease in herbaceous matter in biobales will likely result in higher bio-bale density; this will result in lower handling costs per ton.

The high content of leaves in willow bales was the result of a low cutting height of the biobaler; this resulted in leaves being picked-up by the biobaler during harvest. By setting the cutting height of the biobaler at approximately 30cm the content of leaves can likely be reduced to less than 0.5%, the content of grass and riparian can likely be reduced by 50%. Increasing the cutting height of the biobaler will cause a reduction in the biomass harvested during the first harvest. During the next harvest this reduction in biomass harvested will likely be partially eliminated. This is due to the fact that the largest yield is found in the growth of new shoots and not in growth of the stem.
Another benefit of increasing the cutting height is that the survival rate of willows is expected to increase in case of inundation early in the next growing season.

The high content of grass in samples of WR #3 was probably a result of improper management practices; the harvest intervals were likely too short. Permitting willow vegetation enough time to regenerate and to outcompete herbaceous vegetation will likely result in lower herbaceous matter contents in biobales. Harvest can probably better be executed approximately every 7 years - but the exact time interval is highly depending on the specific willow ring.

Changes to storing

Improper storage of biobales can cause contamination by dirt and increased deterioration of the bottom of the biobales. To maintain the quality of the biobales the storage should take place on a thick layer of flax straw. To keep the handling time of biomass to a minimum the storage of biobales should be located very close to the storage location for shredded biomass. With a small tractor (65HP) bales can be stacked in a 3-2-1 pyramid after which they should be covered with a paper based tarp to secure proper drying.

Changes to processing

Biomass will be custom shredded in a bale shredder after which it is temporarily stored in the first storage bay. After the storage bay is filled the shredder will be located in front of the second bay after which it will be filled with first time shredded biomass. Custom shredding will take place several times throughout the heating season. The pole-shed needs to be capable of storing the total amount of biomass that can be shredded in an 8-hour period – about 240 bales or 500m^3.

Changes to loading

Proper storage of shredded biomass consists of an open-top storage silo located inside the pole-shed. The efficiency of the system will increase as this eliminates the need of using a forage deck, a silage blower as well as a five-ton truck to fill the storage silo.

5. ACCURACY RESULTS

Data collection

During this research data was collected through literature reviews, interviews with biomass experts at the ADC and by doing multiple field experiments. The data collected through the combination of these sources have created an interesting view on the potentials of woody biomass sources in the PPR.

Literature reviews

Literature reviews was implemented during multiple phases of the research. Ample information was found during literature reviews on biomass quality, SRC-and biobaler harvesting systems, current system setup and willow growth characteristics in natural willow rings. The majority of the information regarding the biobaler harvesting system and willow growth characteristics in natural willow rings was found in publications of the ADC. Due to limited information on native willows in the PPR in certain circumstances data from other willow species was used; however, it is expected that this data will be much the same for willows species native to the PPR.

Interviews

During the course of the research lots of information was shared from biomass expert Chris Stefner (ADC) regarding biomass harvest and -processing and the ability of the KÖB Pyrot 300 to handle shredded biomass. Since the ADC is currently the only organisation which derives biomass from natural willow rings with an Anderson Biobaler and processes them with agricultural equipment it was of no additional value to interview other biomass experts. In order to get a full understanding of the system many hours were spent gaining practical experience on each phase of the process. During each phase a lot of time was spent on discussing the noticed issues.

Field Experiments

Field experiments were implemented to determine the herbaceous matter content in biobales and to determine the regeneration, yield and mortality of native willow in willow rings after harvesting activities. Two different trials were set out for collecting the data;

the herbaceous matter content in biobales was determined by sampling a total of 9 biobales

the regeneration, yield and shoot mortality were collected by collecting multiple data sets in a total of 30 sample plots

Even though the number of samples taken to determine the herbaceous matter content in biobales was limited no additional data collection is needed at this time to improve the accuracy since this was mainly done to determine if there was a variation present.

Additional data collection on regeneration, yield and shoot mortality are required to increase the accuracy on the results found in this study. These particular data sets will need to be collected after each harvesting operation

6. CONCLUSIONS

The main research questions were:

What are the effects of repeated harvest activities with an Anderson Biobaler in natural willow rings around prairie wetlands on the regeneration characteristics of natural willows?

Which management tactics can be implemented to increase the efficiency of the biomass harvesting and processing system?

In order to answer those main questions, a variety of sub research questions were posed. The conclusions to this subset of questions are categorized below.

- *Is there a significant change in ratio of herbaceous matter in biobales after natural willow rings have been harvested multiple times in comparison to a first time harvested willow ring?*

Biobales from the first and second time harvested willow rings (WR #1 and WR #2) contained significantly less herbaceous biomass than biobales from the third time harvested willow ring (WR #3) ($p=0.0008$ and $p=0.0001$ respectively). Biobales from WR #1 contained significantly more herbaceous biomass than biobales from WR #2 ($p=0.039$).

- *What effect does harvesting of natural willow rings with an Anderson Biobaler have on the regeneration of shoots?*

An increase in the number of shoots regenerated per m^2 was found by an increase of applied harvests; however, the variance is found to be not significant.

- *What are: the ash content, burning characteristics and moisture content of biomass from harvested natural willow rings?*

The moisture content of biomass from WR #1 was 34.81%, WR #2 13.79% and WR #3 29.63%. The high moisture contents in biomass from WR #1 and WR #3 caused immediate deterioration. Biomass from WR #2 created constant clogging in the in-feed auger system and was therefore found to be incombustible. Biomass from WR #2 had an ash content of 2.98% slightly above average (± 2%) but created high amounts of glass build-up in the combustion chamber. Biomass from WR #3 performed well during combustion but contained 6.14% ash.

- *Which management practices can be implemented to create a more efficient biomass harvesting- and handling system?*

A number of management practices are proposed to improve the harvesting and processing of willow biomass – see 4.8 for more details.

- *What is the mortality rate of shoots during the first growing season of harvested natural willow rings?*

The overall shoot mortality of WR #1 was calculated at 92.01%, WR #2 at 81.52% and WR #3 at 69.06%. This mortality of shoots has predominantly taken place during an early stage of the growing season and was likely caused by long-time inundation.

- *What is the biomass yield for each willow species during the first growing season of harvested natural willow rings?*

Only *S. petiolaris* was found in all three willow rings. Yields for this species were higher in WR #2 than in WR#1 and WR#3; however, the variation was found to be not significant. Long-time inundation likely caused high mortality of shoots in WR #1 which resulted in a lower yield than in WR #2. Growing conditions for *S. petiolaris* were better in WR #2 than in WR #3. It was not possible to determine the differences in biomass yield for the other three species.
The total average annual biomass yield found in the three willow rings ranged from 0.89 to 1.48 odt ha^{-1} y^{-1}.

- *What is the cost of producing wood chips from natural willow rings with the equipment used at the Agroforestry Development Centre, and how does this compare to the cost of fossil fuels?*

The cost of producing wood chips from natural willow rings was calculated at $98.03 / ton when most handling and processing is executed by a contractor. When handling of biobales is executed by the end user the costs can be reduced to $79,10 / ton. In the first case the costs per GJ are slightly higher than that of natural gas. In the second case the costs per GJ would be slightly lower than that of natural gas.

- *Is the KÖB Pyrot 300 successful in handling shredded willow biomass from natural willow rings?*

The KÖB Pyrot 300 wood-fired boiler located at the ADC was found to be unsuccessful in handling shredded willow biomass from WR #2. This biomass was of very high quality: it contained a very low moisture content (13.79%) and very little non-woody biomass (± 2.35%) but it had a very low density (±159.1 kg/m^3). The combination of these characteristics caused continuous clogging in the in-feed auger system.

7. RECOMMENDATIONS

- The research concluded that the quality of biomass highly depends on the presence of non-woody biomass in the willow rings. Guidelines are required to select willow rings that are suitable for high quality biomass production.

- Samples which were taken in September showed that biobales from WR #1 and WR #3 contained very high moisture contents after a nine month drying period. To increase the efficiency of the system it is necessary to decrease the required drying time. Additional research is required to see if drying time for biobales with high herbaceous matter contents decreases if storage finds place underneath a bio tarp.

- Further increase in the quality of biomass derived from willow rings is needed. For this reason research is required to improve the screening of biomass during the processing phase, in order to reduce the content of non-woody biomass.

- To determine the duration between two consecutive harvests close attention needs to be paid to the presence of non-woody biomass. Allowing native willows additional time to outcompete non-woody vegetation will increase the quality of harvested biomass. It is recommended to wait a minimum of five years between harvests.

- Deriving high quality biomass from natural willow rings has proven to be possible. The current wood-fired boiler is not capable of using biomass with these characteristics. For this reason it is recommended to implement the proposed changes to the in-feed auger system (chapter 4.6).

- The possibility of harvesting willow rings greatly depends on weather conditions. High water levels during the harvesting season makes the harvest of certain willow rings impossible. In order to prevent shortages of biomass during years with high precipitation it is recommended to find additional sources of biomass.

Additional research topics

- Effect of decreased harvest intensity on the presence of non-woody biomass in biobales.

- Effect of high water levels on first year yield of harvested willow stools.

- Effect of herbaceous matter, shoot diameter and density of biobales on the speed of drying.

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INDEX OF FIGURES

APPENDIX 1

Overview costs biomass handling and processing

Mostly custom work

Harvesting (self)	
$131.5/hour	
30 bales / hour	
7.5 tons / hour DW	
Cost/ton @ 7.5 tons/hour	$17,53
Loading trailer (custom)	
$125 per hour	
60 bales per hour = 15 tons DW	
Cost/ton	$8,33
Bale transport (custom)	
$120 per hour	
0-50 miles	
Cost/ton	$20,50
Bale stacking (custom)	
$125 per hour	
15 tons DW per hour	
Cost/ton	$8,33
Grinder loading first (custom)	
$125 per hour	
15 tons per hour	
Cost/ton	$8,33
First time shredding (custom)	
Tub-grinding self-propelled $200/hour	
15 tons DW per hour	
Cost/ton (first time shredding)	$13,33
Grinder loading second (custom)	
$125 per hour	
15 tons DW per hour	
Cost/ton	$8,33
Second time shredding (custom)	
Tub-grinding self-propelled $200/hour	
15 tons DW per hour	
Cost/ton (first time shredding)	$13,33
Total	**$98,03**

Mostly own work (own wage $25,-/hour)

Harvesting (self)	
$131.5/hour	
30 bales / hour	
7.5 tons / hour DW	
Cost/ton @ 7.5 tons/hour	$17,53
Loading trailer (self)	
$54,- per hour	
60 bales per hour = 15 tons DW	
Cost/ton	$3,60
Bale transport (custom)	
$120 per hour	
0-50 miles	
Cost/ton	$20,50
Bale stacking (self)	
$54,- per hour	
15 tons DW per hour	
Cost/ton	$3,60
Grinder loading first (self)	
$54,- per hour	
15 tons per hour	
Cost/ton	$3,60
First time shredding (custom)	
Tub-grinding self-propelled $200/hour	
15 tons DW per hour	
Cost/ton (first time shredding)	$13,33
Grinder loading second (self)	
$54,- per hour	
15 tons DW per hour	
Cost/ton	$3,60
Second time shredding (custom)	
Tub-grinding self-propelled $200/hour	
15 tons DW per hour	
Cost/ton (first time shredding)	$13,33
Total	**$79,10**