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COMPARISON OF AGROFORESTRY SPECIES FOR WOODY BIOMASS PRODUCTION

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Abstract: The use of woody biomass is increasing in North America as the economics of fossil fuels change and concerns about climate change grow. *Salix spp.* and *Populus spp.* have been considered to be best for biomass production in temperate regions because of their fast growth. However, there exists little information about other temperate tree and shrub species, including those that are commonly used in western Canada for agroforestry. To determine the potential of such species for biomass production, eighteen commonly used agroforestry species were studied, including *Salix* and *Populus* clones for comparison. Characteristics that were analyzed included leaf and shade development, drought and cold tolerance, timing of growth, ability to regenerate after coppice and the frequency of harvest. Nine of the most promising species were further studied in 2010 for photosynthetic rate, light interception and carbon partitioning. This work was conducted by Camille Herouard as a Master's project for the École Supérieure d'Agriculture of Angers, France. Results will be presented, with a particular focus on the most promising species. For example, red elder (*Sambucus racemosa*) was found to re-grow very quickly in the year after coppice, with aboveground biomass production comparable to acute willow (*Salix acutifolia*). However, biomass growth was less in the second year, partly due to heavy fruit production, suggesting annual coppicing would be advisable. Buffaloberry (*Shepherdia argentea*) and pincherry (*Prunus pensylvanica*) also performed well when harvested at longer intervals. It was not the purpose of this work to identify the fastest-crowing species, as it is clear that willows and poplars have the greatest potential for dedicated woody biomass plantations. Rather, the purpose was to understand the productivity of adapted native, multi-purpose woody species, with a view to developing recommendations for their sustainable use as woody biomass sources in agroforestry systems.

Keywords: coppice, LAI, photosynthesis

INTRODUCTION

In Canada, the Program of Energy Research and Development (PERD) is a federal, interdepartmental program operated by Natural Resources Canada (NRCan), whose aim is to fund research and development for a sustainable energy future for Canada. One of its research themes concerns "purpose-grown woody biomass production".

The purpose of the research described here is to evaluate the potential of different species to grow woody biomass in order to develop agroforestry systems for biomass production and to focus on woody species that are native to the Canadian prairies. The species were evaluated in terms of the physiological and phonological characteristics that contribute to their suitability for biomass production. Seven species have been identified, all native from the prairies, useful in agroforestry systems, and fast-growing. Their potential to grow and produce woody biomass will be studied and compare with willow and poplar, two genus often used in biomass production systems. As biomass production is closely related to photosynthesis rate and efficiency, photosynthesis of each of these species will be carefully analysed.

One of the important characteristics measured in 2010 was photosynthetic capacity. Photosynthetic rate varies among tree species, individuals, and provenances (Pallardy, 2008). The efficiency of photosynthesis is closely related to physiological and genetic characteristics of leaves: their efficiency of using light to produce carbohydrates, their biochemical composition, their stomatal behaviour, their structure, quantity, distribution, duration, etc. These factors are different among species but can also vary within species, between individuals or clones (Pallardy, 2008). These characteristics are mostly genetic but also depend on environmental conditions, which ultimately determine the plant's ability to convert light into carbohydrates (Green *et al.,* 2001; Cannell *et al.*, 1987).

Biomass production was one of the critical characteristics considered. The carbon allocation pattern differs for different species – the distribution of carbohydrates for different processes such as respiration, growth and reproduction, and between various structures of the plants – the roots, leaves, stems and reproductive organs (Kozlowski *et al.*, 1991) and the movement of carbon from "sources" to "sinks" (Pearcy *et al.*, 1991). In trees, age and time of year influence dry matter partitioning. In young trees, a very high proportion of photosynthates are used in leaf production. In older trees, the dry weight is mostly concentrated in the main stem and proportionally less in the crown and root system. New roots and new leaves are the main sinks for photosynthates in spring, but the development of fruits and seeds become stronger sinks later in the year (Kozlowski *et al.*, 1991). For wood production, the maximum of carbohydrates should gather in wood avoiding losses in others organs.

Coppicing or periodic cutting of the tree crown is a harvest practice of importance in woody biomass production because it permits rapid regrowth from established roots without the need for costly field preparation and replanting. Trees can be coppiced at predetermined intervals, depending on species ability to withstand repeated harvests. Species or clones with good or excellent coppicing ability are found within *Salix, Populus, Robinia, Eucalyptus, Alnus* and *Betula* (Mitchell *et al.*, 1992). Willow, one of the main species used in short rotation forestry, can be coppiced repeatedly in a rotation of 3 to 5 years, during 20 to 25 years (Mitchell *et al.,* 1992). Its average biomass production is in between 10 to 12 $tDM.ha^{-1}.yr^{-1}$, and for poplar it is in a range between 10 and 15 $tDM.ha^{-1}.yr^{-1}$ (Vande Walle *et al.*, 2007).

Combining the concepts of canopy development – its leaf area and duration – with the question of photosynthetic efficiency we set out two basic hypotheses: 1) That a good canopy development and long canopy duration will improve light interception and result in more biomass production and 2) That species with high photosynthetic rates have a greater potential to produce biomass.

Through these two hypotheses, we assumed that high biomass potential would be represented by: high Leaf Area Index (LAI), high Leaf Area Duration (LAD), high CO_2 uptake rate and high aboveground wood allocation (compared to other components). The objective was not to identify the only one best species. All of them have potential under different conditions. The objective of this study is therefore to identify the conditions and management under which these species may be suitable.

Allometric relationships that relate biomass to an easily measured parameter such as height or stem diameter are important in order to facilitate quick, non-destructive ways of determining plant biomass. For straight and single-stemmed trees, height and stem diameter are both closely correlated with stem volume (Stewart *et al.*, 1992). For shrubs, diameter measurements are preferred since the correlation between tree height and biomass is often poor. Good correlation has been shown between biomass and diameters at 15, 55, 85 or 105 cm height (Roussopoulos *et al.* 1979; Nordh *et al*. 2003). The simplest allometric equation used to predict biomass (W) from stem diameter (D) is: $W=aD^b$. In this equation, *a* and *b* are parameters related to clone or species and age (Smith *et al*., 1983).

MATERIALS AND METHODS

Species and site

The nine species in Table 1 are all well adapted and suitable to use in agroforestry systems in the Canadian prairies and were evaluated in this study. The trees/shrubs for the study were in two sites at the AAFC-AESB Agroforestry Development Centre in Indian Head, Saskatchewan.

Table 1. List of species evaluated for biomass production

Common Name	Abbr.	Latin Name
Manitoba maple	MM	*Acer negundo* L.
Red-osier dogwood	DW	*Cornus sericea* L.
Green ash	GA	*Fraxinus pennsylvanica* Marsh.
Walker poplar	WP	*Populus hybrid 'Walker'*
Pincherry	PC	*Prunus pensylvanica* L.
Choke cherry	CC	*Prunus virginiana* L.
Acute willow	AW	*Salix acutifolia* Willd.
Red elder	RE	*Sambucus racemosa* L.
Silver buffaloberry	BB	*Shepherdia argentea* Nutt.

At the Horsman Site, green ash (GA), Walker poplar (WP), Manitoba maple (MM), pincherry (PC), choke cherry (CC), buffaloberry (BB) and dogwood (DW) were established in the spring of 2003 and have been used since then for coppice trials. As the last harvest was done in the fall of 2007, the plants in 2010 were in their third growing season. The species are closely spaced (0.5 m) in 5-plant plots in 20 rows with 2.5 m between-row spacing. The species are randomly replicated throughout the site. The soil is a medium-textured, slightly saline loam.

At the V5 Site, red elder (RE) and acute willow (AW) were planted in 2008 for this biomass study. They were in their third years of growth, and had not been coppiced before. They are in square 5-plant by 5-plant plots with 1 m X 1 m spacing. Ten individual plants were selected in two of the most successful plots for evaluation. The soil is a moderately fine-textured clay loam.

Monitoring phenology

Budburst, flowering and fruit development was monitored on ten individual tree/shrubs of the nine species. The observations were done three times per week from April to August. For budburst, the stages were: dormant (0) > activated (1) > green tip (2) > budburst (3) > leaf emergence (4). For flowering and fruit development, the stages used were similar to those of Sherry et al., (2007): no flowers (0) > early flowering (1) > full bloom (2) > petal fall (3) > early fruit (4) > fruit enlargement and ripening (5) > fruit senescence (6). One branch per tree was selected and tagged for repeated monitoring.

Photosynthetic capacity

In order to analyse species' photosynthetic capacity, canopy structure, photosynthetic rate and duration were assessed. This consisted of monitoring the Leaf Area Index (LAI) and Leaf Area Duration (LAD) over the growing season and measuring photosynthetic rates and Light Use Efficiency (LUE) with an ADC LCPro gas exchange (CO_2 and H_2O) meter for all species at selected times of the growing season.

For relative assessment of LAI and LAD, measurements of PAR interception by the canopy were done weekly between April and June for 10 individuals of each species. A SunScan Analyzer was used (Delta-T_UK, type SS1) which is a 1 metre long wand with 64 equally spaced photodiodes, as well as a Beam Fraction Sensor (Delta-T_UK, type BF3). Radiation was measured on sunny days by placing the probe beneath the canopy, on the north side of the tree/shrub, sometime between 10 am and 3 pm. Monitoring was discontinued by June 29th, when the canopies were fully developed and Photosynthetically Active Radiation (PAR) interceptions had become constant. The percent intercepted PAR was calculated by dividing the transmitted PAR by the total PAR, as measured by the BFS, subtracting from 1, and then multiplying by 100.

LAI was sampled at full canopy development on three trees per species by erecting a frame of 21 cm x 21 cm x the tree/shrub height and then all leaves present inside the frame were harvested. The frame was erected at three positions (south, middle, north) inside the canopy of each tree/shrub. The total leaf area was determined for each location by feeding the leaves through the LI-3100 Leaf Area Meter (LI-COR_Lincoln, USA, type LI-3100C) (i.e. 3 harvests x 3 trees x 9 species = 81 harvests). For each species, the average of these nine measurements was calculated and divided by the area of the frame (441 cm^2) to determine LAI.

Photosynthetic rate was determined for ten leaves of each species at the beginning of July, using a portable infrared gas analyser (ADC_UK, type LCpro) to determine gas exchange (CO_2 and H_2O) rates. Measurements were done on 10 different individuals per species. Measurements were done during sunny days, when the temperature was between 25 and 30°C.

Biomass production

All stems at 55 cm above the shoot base were counted and harvested at the end of the growing season for five individual plants of each species. The diameters of the fifteen biggest stems were measured and their fresh weights were determined for allometric analysis (see below). The remaining shoots were weighed in bulk just after harvest. It was therefore possible to know the total fresh weight of each plant. The fresh weight to dry weight ratio was determined from the drying of fifteen stems per species and this ratio was used in calculating the dry weight from the measured fresh weight..

Allometric relationships

As allometric coefficients were difficult to find in the literature for the species used in this study, it was decided to construct our own allometric relationships between stem diameters and shoot dry weight. The methodology reflects that used by Nordh and Verwijst (2004). The diameters of the fifteen biggest stems were measured at 55 cm above the shoot base and their fresh weights were determined. In this way, an allometric relationship of stem diameter to stem biomass could be determined for each species. All remaining stems were counted and harvested and weighed in bulk.

To assess carbon allocation between fruit, wood and leaves, and to determine the relation between fresh and dry wood, three stems were selected from the fifteen biggest ones (a large one, a medium one and a small one). Fruits/seeds were detached from the shoots, and weighed separately (fresh weight). Bags containing 1) wood and leaves and 2) fruits or seeds were dried for one week at 35°C, and then re-weighed. Leaves were removed from the stem and weighed separately. Dry weight of fruits/seeds, woods and leaves were therefore known.

RESULTS AND DISCUSSION

Monitoring phenology

Budburst – Results of leaf development monitoring are presented in Figure 1. According to these results, pincherry was the first species to break bud, although other species such as red elder, Manitoba maple, chokecherry and acute willow broke bud soon afterward. Green ash was the last species to develop leaves, almost a month behind the pincherry. The relative rate of leaf development could be an important determinant of growth, especially for the pincherry, which started early, and the green ash, which started late. For red elder and green ash, leaves developed very quickly, as it took only four days between the beginning of the green tip stage and the beginning of the leaf emergence stage. They are therefore fast to reach a high level of photosynthetic activity.

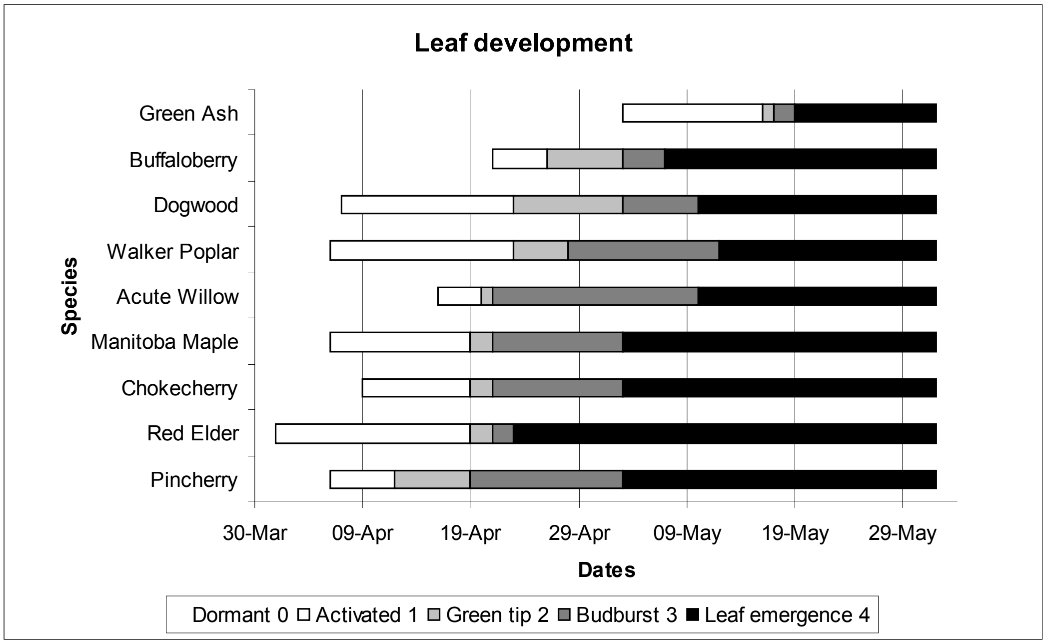

Figure 1. Leaf development of nine species rated by five stages

Flowering and fruit development (Figure 2) – Results were few for this component of the study as only five species had reached their sexual maturity and developed flowers and fruits. For buffaloberry, pincherry and chokecherry, only four or five trees had fruit. Buffaloberry flowered early but fruit development took a long time. Red elder had a large amount of fruit production. Dogwood was unusual because flowering was continuous throughout the summer. Fruit were developing and maturing while new flowers were appearing constantly, making it impossible to assign a particular stage to it.

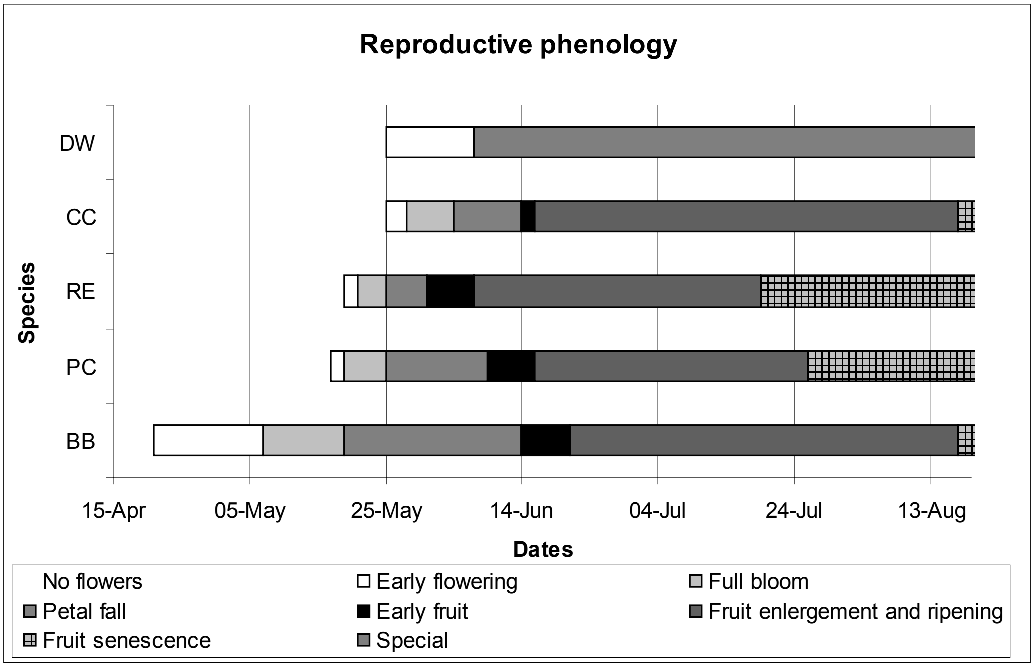

Figure 2. Flowering/fruiting stages for five species. The other species did not produce flowers/fruit.

Photosynthetic capacity

Leaf Area Index (LAI) was significantly different among species, as determined by the frame sampling method (Figure 3). Buffaloberry had a lower LAI than the other species, while red elder, chokecherry and green ash had higher LAI's. The early leaf development of red elder and chokecherry (Figure 1) might combine with higher LAI's, as found here, to suggest the possibility of efficient light capture by these two species.

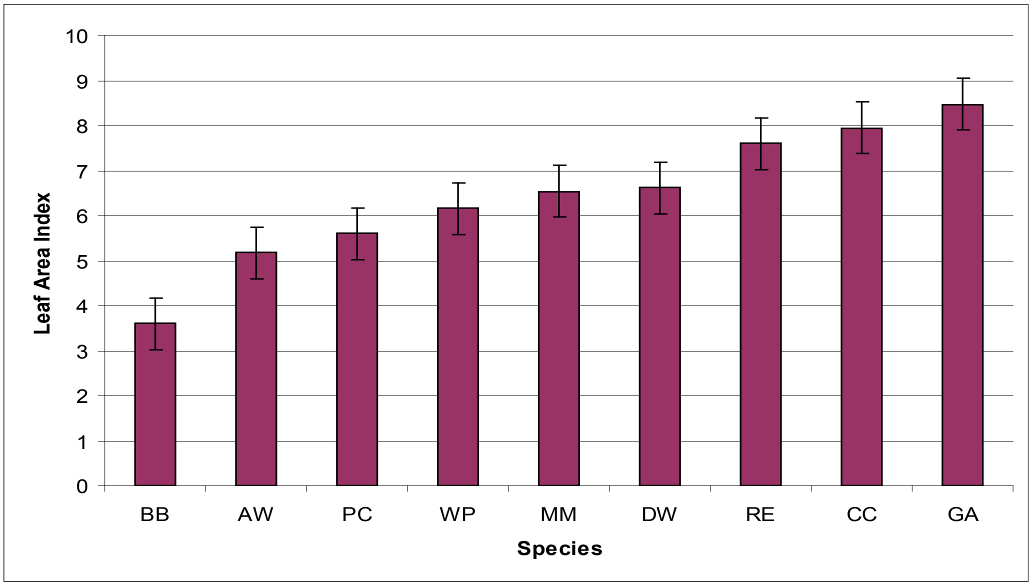

Figure 3. Leaf Area Index, as determined by leaves destructively sampled in a vertical frame.

PAR intercepted by the plant canopies increased at different rates, as expected from the leaf development observations (Figure 4). Increases in light interception were noticeable by May 4, 2010, in chokecherry, buffaloberry and acute willow, while all the other species had developed significantly by May 17th, with the exception of green ash, which began leafing out immediately afterward. The greatest differences among species were seen on May 17th, with chokecherry at the top and green ash at the bottom. The canopy development of green ash lagged behind that of chokecherry by approximately three weeks. The early leaf development observed for pincherry did not translate into a more rapid increase in PAR interception, perhaps due to differences in leaf expansion rates between it and other species like chokecherry.

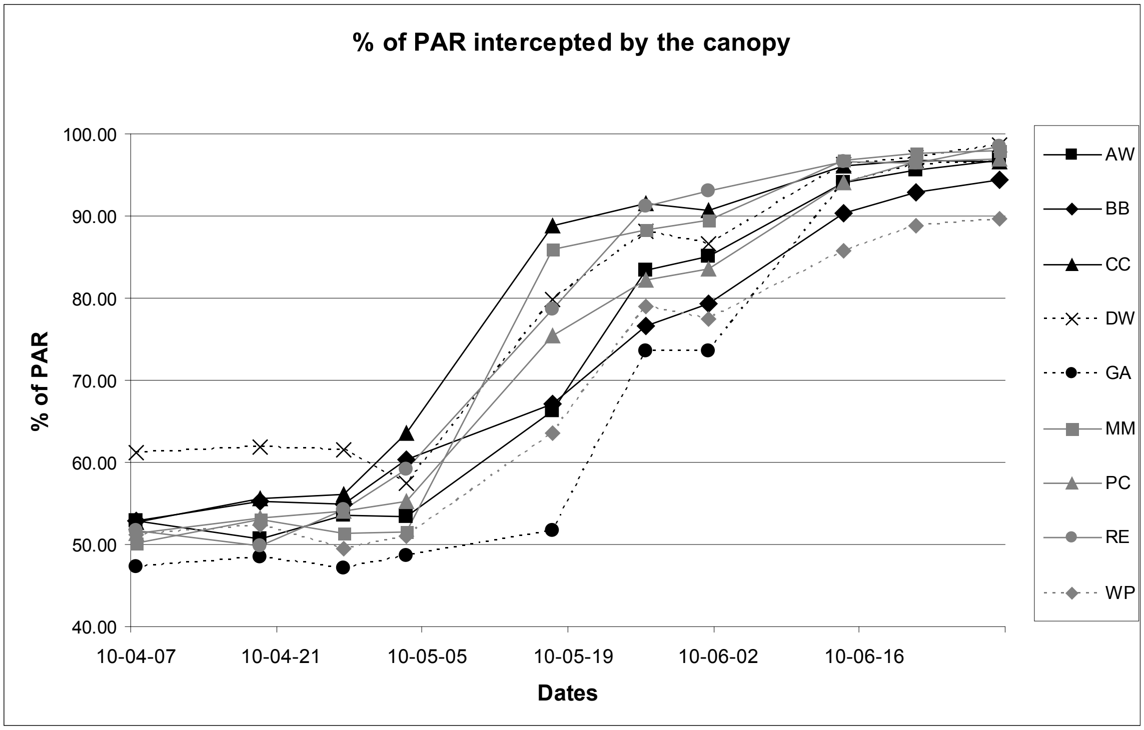

Figure 4. Time course of PAR interception by nine agroforestry species.

Gas exchange rates by leaves were coupled for all nine species. The species that had the highest CO_2 uptake rates also had the highest transpiration rates (Figure 5). The CO_2 uptake rates were of the most interest and showed little difference for the five lowest species. Pincherry and Walker poplar showed significantly higher rates than the five lowest species, with dogwood and acute willow showing just slightly lower uptake rates. As Poplars and willows are the most used species for rapid woody biomass production, these results perhaps show an important reason why, as the CO_2 uptake rate of Walker poplar was approximately 50% higher than that of the lowest five species. These results are of particular interest with respect to the high CO_2 uptake rate of pincherry.

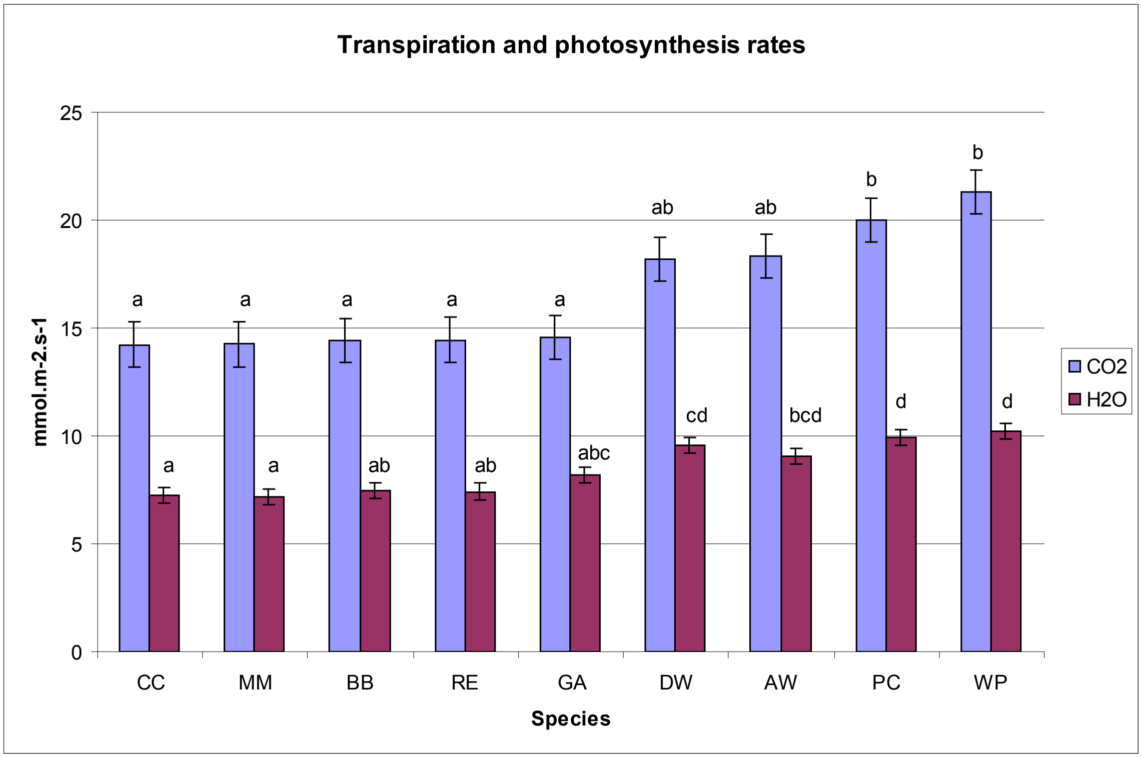

Figure 5. Carbon dioxide and water vapour exchange rates for nine species averaged over all sampling periods.

Biomass production

Some species vigorously re-grow from coppice harvesting. The ability to produce new shoots from adventitious buds, the proximity of roots to shoots and the retention of large parental root system with abundant reserve substances promote this re-growth. However, some species lack the ability to re-sprout quickly and the root systems may not store the reserves necessary for vigorous re-growth. Some shrub species that do not produce a lot of biomass after annual coppicing may produce significantly large amounts of biomass when harvested at longer intervals.

A comparison of aboveground growth after coppice (Figure 6) showed that red elder and acute willow produced the greatest average biomass when coppiced annually, while coppice harvesting was delayed until the third year favoured Walker poplar, which produced more biomass than other species, even more than acute willow after four years. Some shrub species that did not produce a lot of biomass after annual coppicing, produced significantly large amounts of biomass when harvested at longer intervals. These included pincherry, sea buckthorn and buffaloberry.

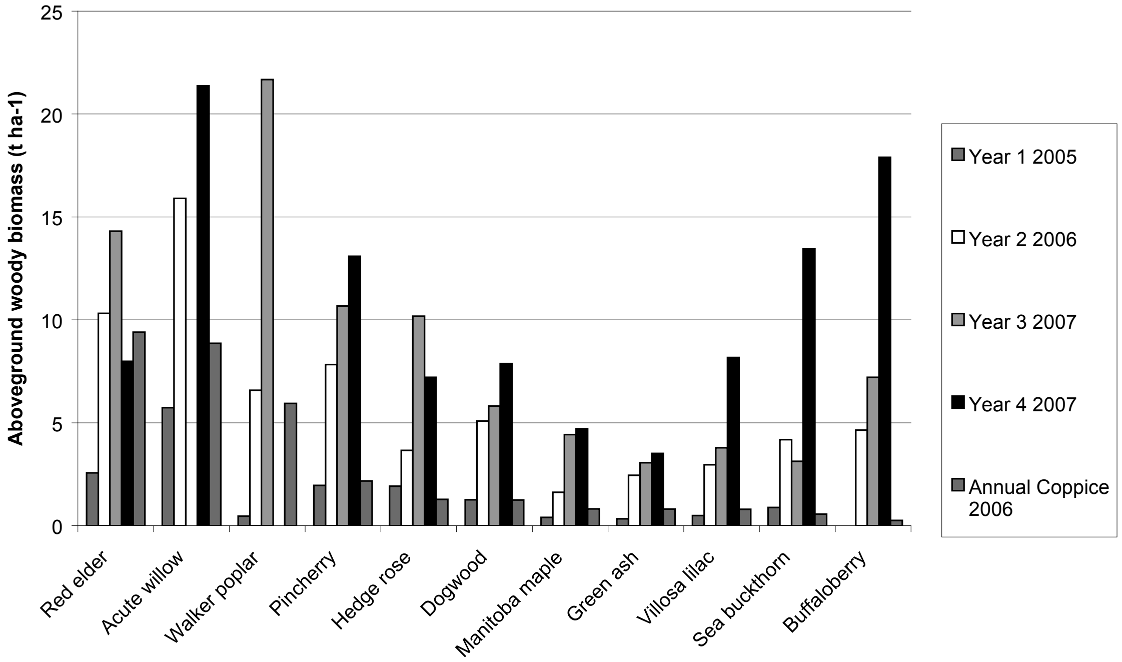

Figure 6. Woody biomass production aboveground for different species after different coppice harvest intervals. Note that some data are missing due to the lack of trees/shrubs to harvest in that age category (e.g. Year 3 for acute willow and Year 4 for Walker poplar).

Dry weight was calculated from measured fresh weight, based on the conversion factors in Table 2, which were determined from the drying of 15 stems per species. Some species, like green ash and chokecherry, had greater dry weight – to – fresh weight ratios than others, like acute willow. The harvested dry biomass varied greatly among species with pincherry, buffaloberry, chokecherry and green ash at the low end and acute willow, red elder and Walker poplar at the high end (Figure 7).

Table 2. Fresh weight to dry weight conversion factors.

Species	Equations (y = dry weight, x = fresh weight)	R^2
AW	y = 0.3565x	0.9714
BB	y = 0.3986x	0.999
CC	y = 0.5363x	0.9972
DW	y = 0.44x	0.948
GA	y = 0.5471x	0.9969
MM	y = 0.4315x	0.9989
PC	y = 0.4728x	0.997
RE	y = 0.427x	0.9865
WP	y = 0.499x	0.999

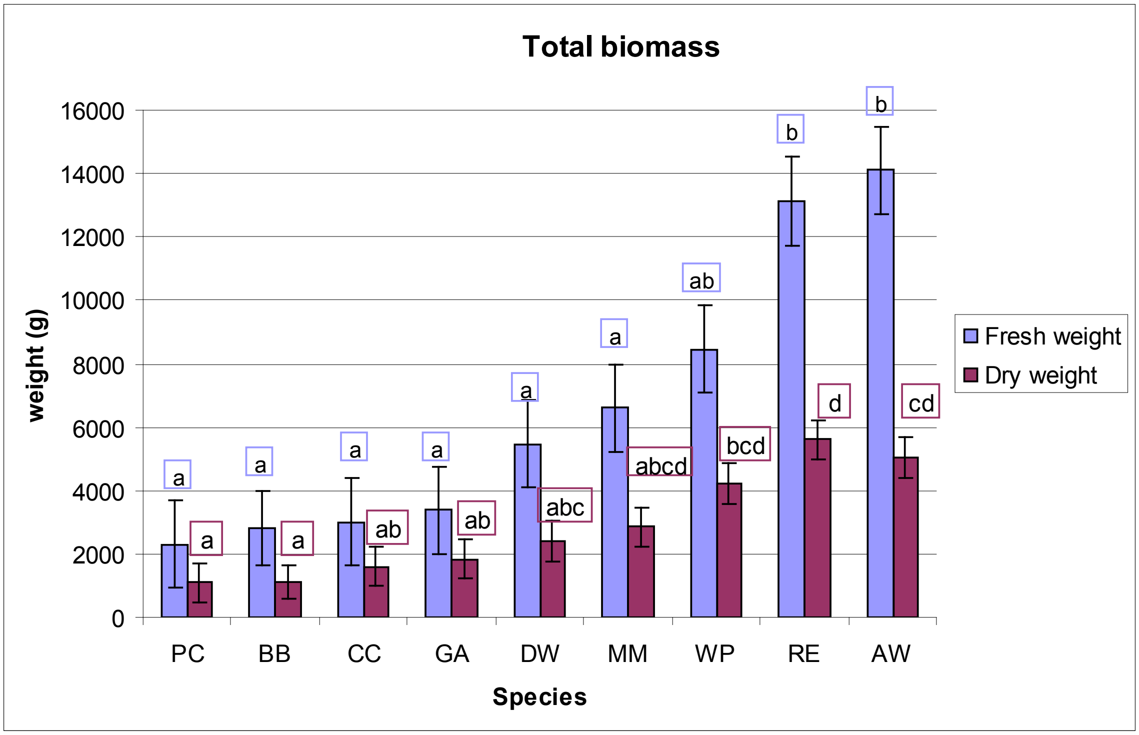

Figure 7. Average biomass of harvested plants for nine species.

Carbon was partitioned differently between species (Figure 8). Only dogwood and red elder had a significant amount of fruit. This perhaps could change over time as fruiting species like chokecherry and pincherry divert more of their resources into fruit. Generally, around 60% of the carbon was allocated into the wood, except for dogwood (46%), which was the lowest, and Walker poplar (78%), the highest.

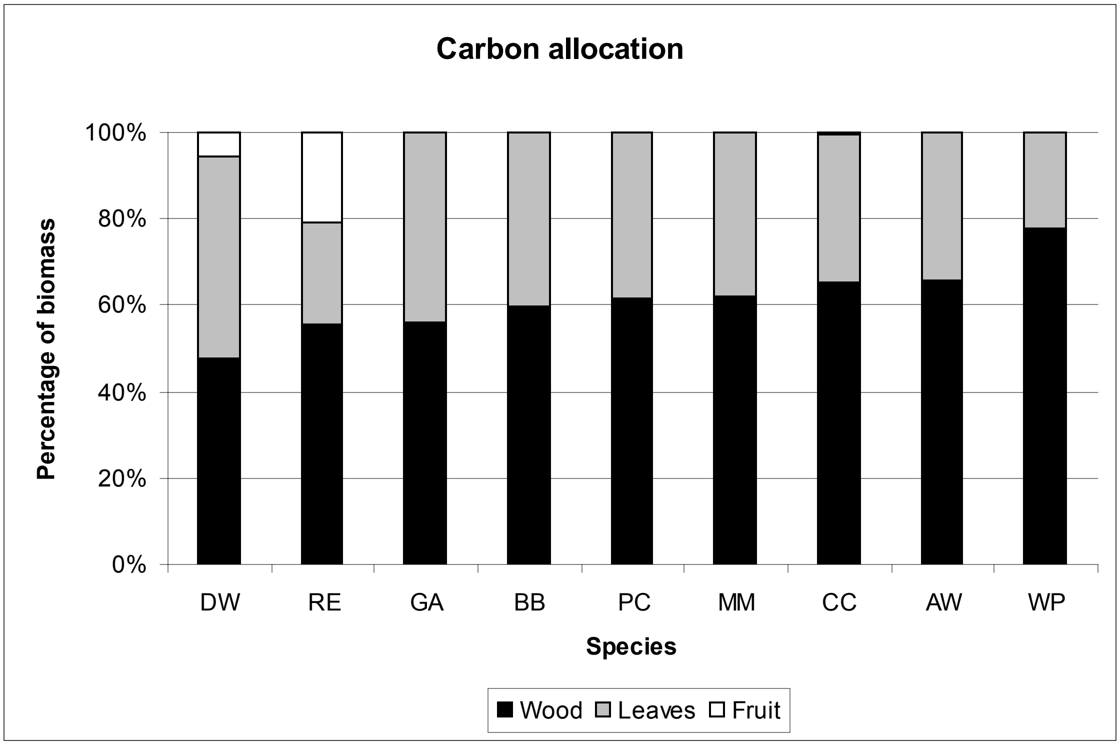

Figure 8. Partitioning of biomass into wood, leaves and fruit.

Allometric relationships

A power regression analysis was done to establish the allometric relations ($W=aD55^b$) between the diameter of the stem in mm and its dry weight in grams (Table 3). The R^2 values tended to be higher for those species having fewer stems and fewer branchings above 55 cm (green ash, Walker poplar) than those with many stems (acute willow, red elder).

Table 3. Results of regression of dry biomass on stem diameter at 55 cm height for nine species

Species	Equations (y = W = dry weight in g) (x = D55 =diameter in mm)	R^2
AW	$y = 0.1572x^{2.5245}$	0.8697
BB	$y = 0.1034x^{2.7751}$	0.9591
CC	$y = 0.1576x^{2.543}$	0.9591
DW	$y = 0.2358x^{2.384}$	0.91
GA	$y = 0.0494x^{3.0052}$	0.9681
MM	$y = 0.0437x^{2.9041}$	0.9613
PC	$y = 0.0882x^{2.8021}$	0.9476
RE	$y = 0.1727x^{2.5283}$	0.674
WP	$y = 0.0669x^{2.7078}$	0.9895

Analysis per species

The nine agroforestry species were assessed for characteristics that were thought to relate to their suitability to biomass production, including canopy development that allows good light interception and a high photosynthetic rate, coupled with a high degree of partitioning of carbon to wood. Table 4 synthesizes the results of every species. Desirable characteristics are represented by "+" and less desirable characteristics by "-". Species were separated in three groups. The first group includes the species that had more than 5kg of biomass per plant – acute willow, Walker poplar and red elder. The second group – Manitoba maple and dogwood – produced an intermediate amount of biomass. The last group consisted of buffaloberry, green ash, pincherry and chokecherry, which produced less than 2kg of biomass. Among this group, pincherry and chokecherry produced more biomass than green ash and buffaloberry.

Table 4. Summary chart of species characteristics. Desirable characteristics are represented by "+", "++" and "+++" - increasing desirability and "-", "--" and "---" – decreasing desirability.

		Group 1			Group 2		Group 3			
		WP	AW	RE	MM	DW	PC	CC	BB	GA
Canopy development and light interception	Phenology	-		++			++			---
	Sunscan (start date)				++			++		---
	Sunscan (%)	---		+++	+	+++			-	
	LAI		-	+++	+	+	-	+++	---	+++
Photosynthetic rate	Gas exchange	+++	+	-	-	+	+++	-	-	
Biomass	Dry biomass	+	+++	+++		-	---	---	---	---
	Carbon allocation	+++		--		--				--

In the high biomass Group 1, the fastest growing species, acute willow and Walker poplar had no advantages in crop development, but had higher-than-average CO_2 uptake rates, and Walker poplar allocated a larger portion of its aboveground biomass to wood that the other species. The high biomass accumulation of red elder, the third species in the group, could be attributed to rapid canopy development and high LAI at mid-season. The species in Group 2, Manitoba maple and dogwood, both had advantages in early canopy development and somewhat higher LAI. Of the species in Group 3, pincherry and chokecherry both had advantages in early canopy development and chokecherry had a high LAI, while pincherry had a high gas exchange rate. Despite this, neither species developed a large amount of woody biomass in 2010. The low biomass production of green ash could be attributed to its late leaf development, which was about three weeks behind that of the earliest species.

Coppicing ability varied among species. Surprisingly, species that normally grow into trees (green ash, Manitoba maple, acute willow, Walker poplar) re-grew quite well after coppice harvesting. Red elder and acute willow seem quite well adapted to annual coppicing, while acute willow gave high biomass when harvested in any year from one to four. Performance of red elder started to decrease after the second year. Because of precocious fruiting in red elder in the second year after coppicing, it appears that annual coppicing would be the best choice for this species. It is not known for how many years this practice could continue without replanting. Walker poplar re-grew best when the cutting cycle was three years between harvests.

Root systems should be also analysed as it contains significant biomass. Pincherry, chokecherry and buffaloberry are suckering species and underground growth may explain some of the lack of aboveground growth of these species. Thus, there may be other important factors that explain the variability in biomass production. The use of growth models or plant architecture representation software such as AMPAmod may help to explain the relative growth of the species.

Agroforestry systems and their adaptation for biomass production

Agroforestry buffers are normally understood to have multiple functions. Even though they may be established for one reason, such as wind protection, for riparian protection or for wildlife habitat, their other benefits may be substantial. The carbon sequestration role of agroforestry buffers has long been appreciated, but the planned harvesting of such buffers has generally not been done.

Recent, deliberate multi-functional "ecobuffers" designs that have been developed by the Agroforestry Development Centre, represent an opportunity to integrate a biomass function into agroforestry buffers. Coppice harvesting of such buffers at appropriate intervals could also help to prolong the useful lifespan of such a buffer, as many older shelterbelts that were planted in the last century have decayed or begun to decay because of their age and the lack of maintenance. Including coppiceable suckering species such as buffaloberry, chokecherry and pincherry, even if they are not the highest biomass-producing species may give such "ecobuffers" the longevity and continued usefulness that may not accrue to more traditional buffer designs.

If rotational coppicing can be practiced, the wildlife habitat value of a buffer will remain intact and the domination of the buffer by a single species may be prevented or delayed.

CONCLUSION

The objective of this study was to understand the growth habit of different native species, in order to develop, in the next years, multi-functional agroforestry systems, both with environmental, social and economical values. The characteristics that have been observed this year are interesting, but more work is needed to explain or assess the biomass production potential of these species. Utilisation of plant architecture software or plant growth models could be useful to reach this objective. ADC plans to continue this species evaluation using the model AMAPmod or another appropriate model.

At the same time multi-species, multi-functional "ecobuffers" are being established in various sites and one of their characteristics that will be monitored over time will be their biomass. More species evaluations could then be carried out, to study their adaptation and resistance to repeated coppice harvest.

The development of a carbon market and the growing interest for bioenergy seem to ensure a favourable future for trees in the fight against climate change, either by acting as a carbon sink or as a source or renewable and green energy.

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