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Sapflow of hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry 'NM6') during phytoremediation of landfill leachate

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Abstract

Poplars are ideal for phytoremediation because of their high water usage, fast growth, and deep root systems. We measured in 2002 and 2003 the sapflow of hybrid poplars (*Populus nigra* L. × *P. maximowiczii* A. Henry 'NM6') planted in 1999 for phytoremediation of a landfill in Rhinelander, WI, USA (45.6°N, 89.4°W). Mean sap velocity per tree was 100 ± 10 and $120 \pm 10\,\mu m\,s^{-1}$ for 2002 and 2003, respectively. Mean sapflow per tree was 1.4000 ± 0.1698 and $5.6760 \pm 0.2997\,kg\,h^{-1}$ for 2002 and 2003, respectively. Sapflow was negatively correlated with temperature, wind speed, precipitation, and vapor pressure deficit for both years ($0.002 < r^2 < 0.61$). Sapflow increased as mean sapwood area increased from 43.8 ± 2.6 to $122.3 \pm 7.6\,cm^2$ for 2002 and 2003, respectively ($r^2 = 0.88$). Individual-tree extrapolations using the mean tree approach were: 34 and 136 kg $tree^{-1}\,d^{-1}$ for 2002 and 2003, respectively, and 612 and 2 448 kg $tree^{-1}$ 18-d^{-1} for 2002 and 2003, respectively. Extrapolations to the stand were 2.8 and 11.3 mm d^{-1} (28.3 and 113.3 Mg $ha^{-1}\,d^{-1}$) for 2002 and 2003, respectively (assuming 833 trees ha^{-1}), and 354 and 1 416 mm yr^{-1} (3.54 and 14.16 Gg $ha^{-1}\,yr^{-1}$) for 2002 and 2003, respectively (assuming a 125-d growing season). Thus, we believe NM6 and other superior-performing poplar genotypes exhibit great potential for phytoremediation applications where elevated water usage is critical.

Keywords: Short-rotation woody crops; Transpiration; Water-use; Granier method; Thermal dissipation method; Sapwood; Phreatophytes

1. Introduction

Phytoremediation (plant-enhanced bioremediation) involves the direct use of living green plants for in situ containment, degradation, or removal of contaminated soil, sludges, sediments, and water [1–5]. *Populus* species and hybrids (hereafter referred to as poplars) have proven successful for remediation of sites with contamination from landfill leachates, petroleum sludges, salts, heavy metals, pesticides, solvents, explosives, and radionuclides [6–12]. Poplars have great potential to successfully control the movement of or decrease the mass of the contaminant [10,13–15]. Poplars filter, trap, degrade, and/or confine the contaminants at less than half the price of other established technologies [16–18]. Poplars are well suited for phytoremediation because they have high water usage, fast growth, and deep root systems [7,19–22].

Sapflow has been accepted as the best surrogate measure for plant water usage [23,24]. Heat is used often as an indicator of the rate of sapflow in trees [25,26]. Three methods commonly used to directly measure tree sapflow in situ using heat as a tracer are: (1) heat pulse, (2) heat balance, and (3) thermal dissipation. The thermal dissipation method is based on the theory and techniques of Granier [27–29], where the sapflow is empirically determined from a temperature difference of sapwood between two sensors located a fixed distance apart along the stem [30]. Therefore, the thermal dissipation method utilizes continuous heating of the stem. Advantages of the thermal dissipation method compared with the heat pulse and heat balance methods are lower costs (a great deal of which are associated with ease of installation), ease of data recording from the sensors to a datalogger, and subsequent ease of empirical sapflow calculations [25,31].

Water usage of poplars is especially important for remediation of sites adjacent to water, such as landfills near rivers and streams, because transpiration of polluted

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groundwater aids in hydraulic control or removal of the contaminant [15]. However, there are limited reports of sapflow in poplars used for phytoremediation. Nevertheless, such knowledge could contribute substantially to the success of poplar-based phytoremediation systems, especially when the objectives of the remediation include the use of poplars as a hydraulic filter of the contaminants. For example, the overall objective of establishing poplars on the landfill in the current study was to provide a hydraulic barrier between the landfill and a nearby wetland. The landfill leachate resulted from precipitation leaching through the porous cap. Thus, the general objectives of the trees were to volatize most of the precipitation before it completely leached through the landfill content and to filter the remaining leachate as it emerged from the edge of the landfill and began to enter the wetland. The specific objective of the current study was to measure sapflow of hybrid poplars planted for phytoremediation of the landfill. We assert this information is important for future managers planning similar poplar-based phytoremediation where hydraulic control, volatilization, and filtering are necessary for overall success.

2. Materials and methods

2.1. Site description

The study site was located at the former City of Rhinelander landfill in Rhinelander, WI, USA (45.6°N, 89.4°W) (Fig. 1). The landfill was adjacent to a wetland that was near the Slaughterhouse Creek, which drains into the Pelican River in Oneida County and ultimately the Wisconsin River. A gravelly, mixed-soil cover, 30–60 cm deep, was placed on the landfill in the late 1980s to function as a cap. Poplars and willows were planted over portions of the cover in 1999 for phytoremediation of landfill leachate, with the leachate potentially being associated with elevated levels of ammonia (NH_3^+) in the adjacent wetland.

The mean winter daytime temperature at the site is 7.8 °C with a mean snowfall of 144.8 cm, while the mean summer daytime temperature is 25.6 °C with a mean rainfall of 61.0 cm. In addition, the mean annual number of growing degrees days (GDD, 10 °C) is 1863, with 544 occurring in July and 480 in August.

Two poplar genotypes were planted for the phytoremediation system. The first genotype was an F_1 hybrid (clone NM6) between European black poplar (*Populus nigra*) and Japanese poplar (*P. maximowiczii*), while the second clone (Eugenei, a.k.a. DN34 and NC5326) was an F_1 hybrid between eastern cottonwood (*P. deltoides* Bartr. ex Marsh) and *P. nigra*. However, Eugenei was not sampled for sapflow because trees of this genotype exhibited diameter less than 10 cm at a height of 15 cm. Trees were planted at a spacing of 3 m within rows and 4 m between rows, with alternate rows consisting of a single genotype. The rows were planted along elevation contours of the landfill cover,

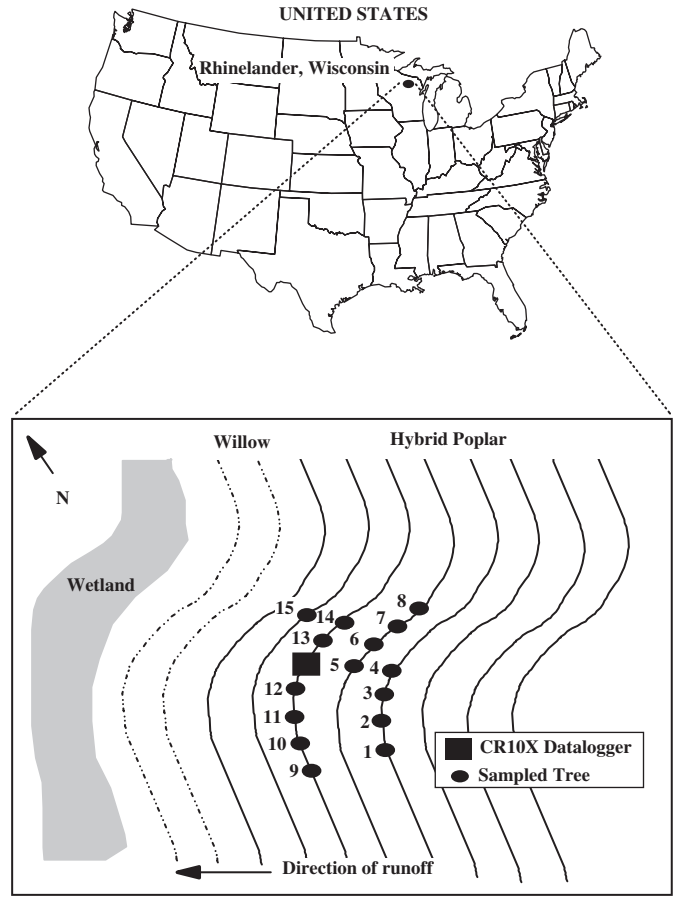

Fig. 1. Location of the City of Rhinelander landfill (Rhinelander, WI) and diagram of test plot in a phytoremediation study during 2002 and 2003 using hybrid poplar trees (*P. nigra* L. × *P. maximowiczii* A. Henry 'NM6') planted in 1999. Poplar rows shown are for clone NM6 only. For simplicity, rows of clone DN34 alternating with NM6 are not illustrated. Sapflow was measured on sampled trees by using 30-mm thermal dissipation probes (TDP30, Dynamax, Inc., Houston, TX) according to the method of Granier [27–29]. There were 15 and 9 trees sampled in 2002 and 2003, respectively.

so the rows were aligned perpendicular to the direction of surface runoff and assumed groundwater flow off the site. Trees were trickle-irrigated almost every day beginning around 0700 HR.

2.2. Climatic measurements

Temperature (°C), dew point temperature (°C), wind speed ($km\,h^{-1}$), and precipitation ($cm\,d^{-1}$) were directly measured at a regional airport weather station (KRHI) located approximately 5 km west from the Rhinelander landfill test site. Vapor pressure deficit (kPa), a secondary variable, was estimated from vapor pressure and temperature according to the methods of Murray [32] and Prenger and Ling [33].

2.3. Biometric measurements

Diameter of the test trees at 15 cm above the ground was determined on Julian Days 154 and 262 during 2002 and

2003. These diameters were used to calculate growth rates for each tree by dividing the difference between diameters by 108 days. The growth rates were multiplied by the number of days since day 154 and added to the diameter at day 154 to estimate the diameter at each of the 18 sampling days. The radius at each sampling day was used for estimation of the cross sectional area of sapwood (cm^2) of each tree, assuming the cross section was a circle. We assumed sapflow occurred equally across the entire sapwood area.

2.4. Sapflow with the thermal dissipation method

2.4.1. Nomenclature

We have described sapflow measurements according to nomenclature proposed by Edwards et al. [34] and later utilized by Vertessy et al. [35] and Clearwater et al. [26]. Thus, sap velocity describes the speed of water movement through the stem, expressed in $\mu m\,s^{-1}$, and sapflow describes the volume of water movement through the stem over a specified time period, expressed in $kg\,h^{-1}$. Stand-level estimates are given in mm, Mg, and Gg per unit land area.

2.4.2. Field installation and data collection

We measured sapflow using thermal dissipation probes (TDP30, Dynamax, Inc., Houston, TX). The probes, each 30 mm long, 1.2 mm wide, and spaced 40 mm apart vertically, were installed into the sapwood of 16 trees of clone NM6 during May of 2002 and 2003, according to the manufacturer's instructions, with one exception. The thermal dissipation probes were installed at 15 cm above the ground and below all branches on trees exceeding minimum diameter (10 cm at 15 cm above the soil surface). Thus, total water usage of the trees was measured, assuming negligible stem water storage [36]. The 30-mm probes were used because of reported recommendations to ensure the entire probe was in contact with the active sapwood in order to reduce experimental error [26]. One set of probes was installed on each tree, which was sufficient given symmetry of the xylem of clone NM6 and greater reported variation among trees than within trees [35,37–39].

Data from 15 and 9 trees in 2002 and 2003, respectively, are reported here. Measurements were collected by using Campbell CR10X dataloggers (Campbell Scientific, Inc., Logan, UT) across 18 d (Julian Days 206–223). These dates were chosen because they represented a substantial portion of the growing degree days throughout the growing season in northern Wisconsin (see description above), and because they generally represented the mean sapflow in other studies of *Populus* [15,40–43]. Temperature difference values were recorded every 10 s and averaged across intervals of 30 min from 0000 to 2400 HR, daily. Data were collected on a weekly basis. Sap velocity and sapflow were empirically calculated by using the aforementioned thermal dissipation method of Granier [27–29].

2.5. Statistical analyses

Linear regressions according to SAS® (PROC REG) [44] were used to examine the relationships between daily average sapflow and temperature, wind speed, precipitation, vapor pressure deficit, and cross sectional area of sapwood.

3. Results and discussion

3.1. Climate

Climatic data are presented in Fig. 2. The mean temperature across the sampling period was 19 °C for 2002 and 2003. The maximum and minimum temperatures across the sampling period for both years exhibited similar trends except for a broader discrepancy between temperatures for 2002. Generally, wind speed was faster in 2002 than 2003. Mean wind speed for 2002 and 2003 was 8 and $5\,km\,h^{-1}$, respectively. Total precipitation across the sampling period in 2002 and 2003 was 3.24 and 8.43 cm, respectively. Vapor pressure deficit averaged across the sampling period in 2002 and 2003 was 0.63 and 0.58 kPa, respectively.

3.2. Tree diameter and sapwood area

In 2002, tree diameter at Julian Day 154 ranged from 4.6 to 7.1 cm, with a mean of 5.6 ± 0.2 cm. On Julian Day 262 diameter ranged from 7.8 to 10.7 cm, with a mean of 9.2 ± 0.3 cm. Interpolated cross sectional area of sapwood at Julian Day 205 (1 day before sapflow measurements began) ranged from 31.1 to 59.5 cm^2, with a mean of $43.8 \pm 2.6\,cm^2$. In 2003, tree diameter at Julian Day 154 ranged from 10.0 to 13.1 cm, with a mean of 11.4 ± 0.4 cm. Likewise, at Julian Day 262 diameter ranged from 11.9 to 15.7 cm, with a mean of 13.7 ± 0.4 cm. Interpolated cross sectional area of sapwood at Julian Day 205 ranged from 93.2 to 161.4 cm^2, with a mean of $122.3 \pm 7.6\,cm^2$.

3.3. Sapflow

3.3.1. Individual tree sapflow

Sapflow increased between years due to increased tree size. Sap velocity per tree in 2002 ranged from 50 to $210\,\mu m\,s^{-1}$, with a mean of $100 \pm 10\,\mu m\,s^{-1}$. In 2003, sap velocity per tree ranged from 90 to $150\,\mu m\,s^{-1}$, with a mean of $120 \pm 10\,\mu m\,s^{-1}$. In 2002, mean sapflow per tree ranged from 0.4962 to $2.5501\,kg\,h^{-1}$, with a mean of $1.4000 \pm 0.1698\,kg\,h^{-1}$, while in 2003 mean sapflow per tree ranged from 4.5581 to $6.9553\,kg\,h^{-1}$, with a mean of $5.6760 \pm 0.2997\,kg\,h^{-1}$. Thus, the sapflow was four times greater with the trees in their fifth growing season relative to those in their fourth growing season. Equivalent sap velocity between years shows that the three-fold increase in sapflow volume was due to the trees growing larger, which was exhibited by a three-fold increase in cross sectional

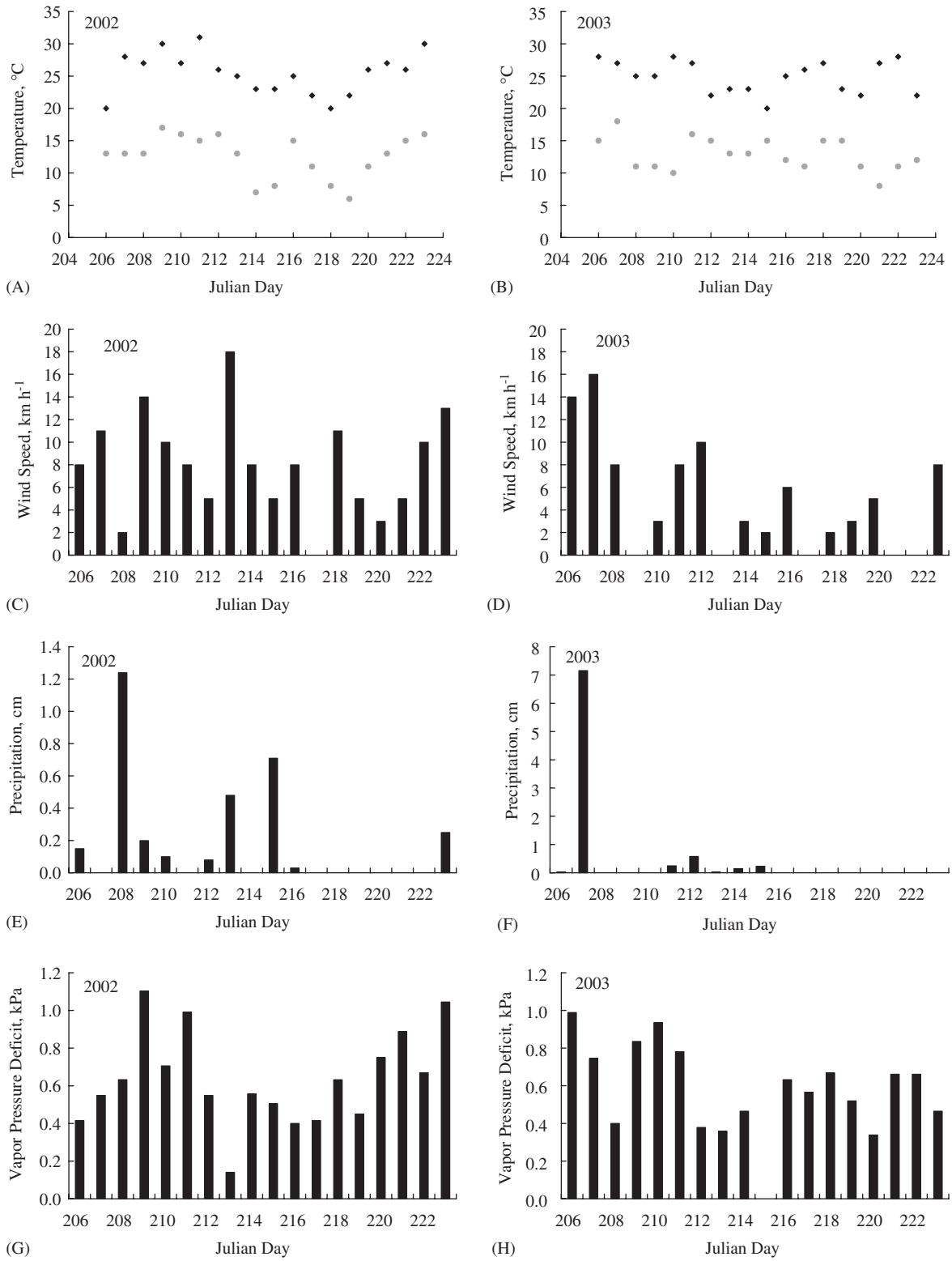

Fig. 2. Maximum and minimum temperature, wind speed, precipitation, and vapor pressure deficit in 2002 and 2003. The data from (A)–(F) were collected at a regional airport weather station (KRHI) located approximately 5 km from the Rhinelander landfill test site. Vapor pressure deficit was estimated according to the methods of Murray [32] and Prenger and Ling [33]. Wind speed and vapor pressure deficit values are 24-h means, while precipitation is the total over each 24-h period. Note the scale change in (E) and (F).

area of sapwood from 2002 to 2003 (previous paragraph). Supporting this trend, Vose et al. [41] reported mean sapflow per tree across the growing season of 0.61 kg h^{-1} for 1-year-old *P. deltoides*. The sapflow during July and August of their trees, ranging in diameter from 6.2 to 9.8 cm, ranged from approximately 0.6 to 0.7 kg h^{-1} $tree^{-1}$.

Furthermore, Knight et al. [45] reported a maximum sapflow of 3.5 kg h^{-1} for a 100-year-old lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) tree with a diameter of 24 cm.

The increase of sapflow from 2002 to 2003 also is exhibited when averaged across trees for each Julian Day (Fig. 3). The mean sapflow in 2002 and 2003 averaged 1.3998 ± 0.0650 and 5.8563 ± 0.3941 kg h^{-1}, respectively. These results indicated an even greater potential for increased rates of water usage as the trees increased belowground and aboveground productivity during growth and development. The best explanation for increased sapflow in 2003 is that greater sapflow occurred because stem area and leaf area increased as the trees grew. The root systems also may have become extensive enough to come into closer or direct contact with the water table. However, similar sap velocities make this rooting assertion less valid. Nevertheless, future studies of this nature should be designed to conduct excavation and observation of root systems.

Sapflow exhibited interesting diurnal patterns. Contrary to results reported by numerous researchers [28,30, 43,45–49], our attempt to relate sapflow with time of day met with uncertain results for 2002. Based on available literature and physiological sapflow theory, we expected bell-shaped curves for sapflow over the daily sampling time of 0800–2200 HR, with the peak sapflow occurring near 1200 HR. However, in 2002 our data exhibited peak sapflow at 0800 HR and decreasing sapflow thereafter (Fig. 4A.). Granier [29] reported a similar trend in *Pseudotsuga menziesii* trees that were irrigated after purposefully being exposed to drought conditions. These trees exhibited peak transpiration levels approximately one hour following irrigation. Likewise, Kaufmann [50] reported peak sapflow of Monterey pine (*P. radiata* D. Don) at 0630 HR and decreasing sapflow thereafter when the trees were subjected to limited soil water availability. Thus, given the drought conditions during the sampling period in 2002, the diurnal trend of sapflow may be the response of our trees to watering following periods of limited water availability. The onset of irrigation each morning may have produced a temporary water surplus, which was associated with elevated levels of sapflow. The sapflow most likely decreased the rest of the day as this surplus was being depleted [28]. Although transpiration decreased into each evening and throughout the night, some levels of transpiration were taking place in order to facilitate sapwood recharge (i.e. rehydration of sapwood after periods of water loss) [45,51]. Pezeshki and Hinckley [52] reported that stomata of *P. trichocarpa* did not completely close during the night, when growing under field conditions. Nevertheless, we assert a substantial portion of the water absorbed by the trees was from the groundwater aquifer, given the development of extensive root systems of clone NM6 [53–55].

Moreover, the diurnal variations in sapflow for 2003 better represented our expected bell-shaped curve

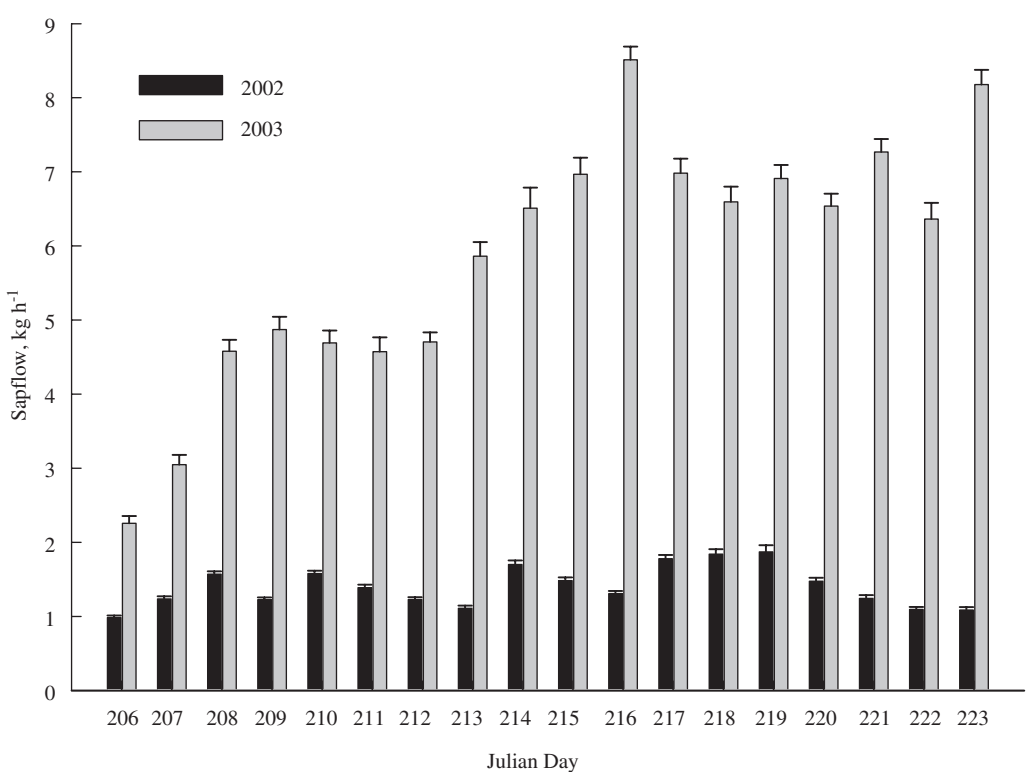

Fig. 3. Sapflow of hybrid poplar trees (*P. nigra* L. × *P. maximowiczii* A. Henry 'NM6') planted in 1999 for each Julian Day across 18-d sampling periods in 2002 ($n = 15$) and 2003 ($n = 9$). Data were recorded every 10 s and averaged across intervals of 30 min beginning at 0000 HR and ending at 2400 HR, daily. Bars represent one standard error of the mean.

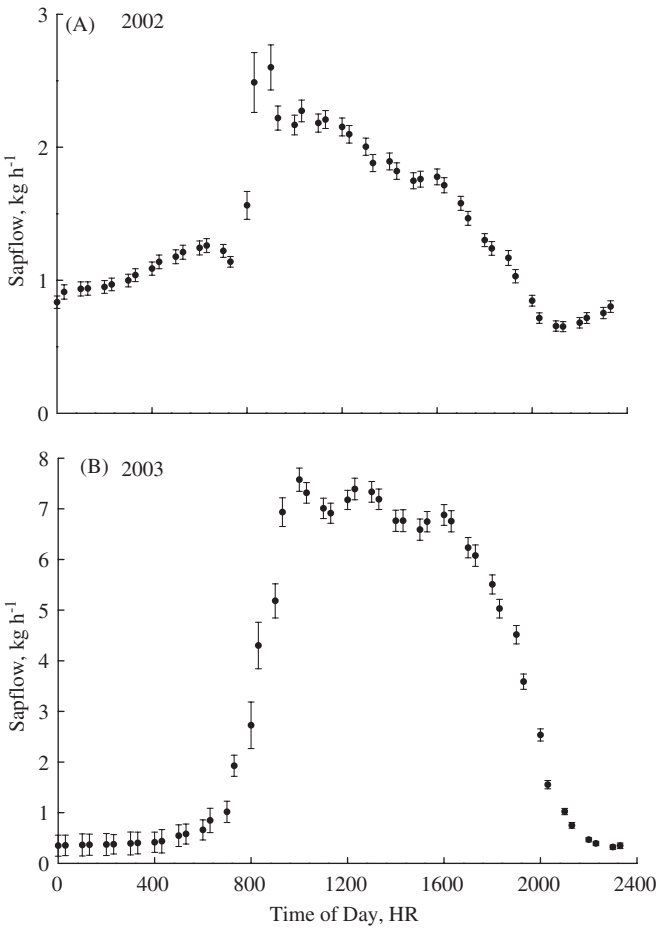

Fig. 4. Diurnal variations in sapflow of hybrid poplar trees (*P. nigra* L. × *P. maximowiczii* A. Henry 'NM6') planted in 1999. Each point represents the mean of 270 and 162 observations in 2002 and 2003, respectively. Time of day is listed in central daylight saving time. Bars represent one standard error of the mean. Note the scale change for sapflow.

(Fig. 4B.). Sapflow increased from 0800 to 1000 HR, peaked just after 1200 HR, and then began decreasing after 1600 HR. We believe the primary reason for this difference in diurnal sapflow is the productivity increase from 2002 to 2003 in belowground and aboveground biomass of the trees, which provided a larger surface for water uptake, conductance, and transpiration. As the trees became large enough for canopy closure to take place, there was an increase in the water load required throughout the entire day. The root systems in 2003 most likely developed large enough to reach the ground water and, coupled with the increase in cross sectional area of sapwood and greater leaf surface area for transpiration, were able to use water longer into the day than in 2002.

3.3.2. Climate × sapflow interactions

Linear models from the least-squares regression analysis relating sapflow with temperature, wind speed, precipitation, and vapor pressure deficit explained the relationships best for all variables, according to coefficients of determination and significance probability values of each regression. However, interpretations must be made with an err of caution given expected variability between the study site and the site of the environmental monitoring station, which were located 5 km from one another.

Trends in 2002 and 2003 relating sapflow and temperature were similar, with a decrease in sapflow as temperature increased (Figs. 5A and B.). However, the slope of the 2002 regression was less than that for 2003. In addition, there was a decrease in sapflow as wind speed increased for both years (Figs. 5C and D.). Once again, the slope of the 2002 regression was less than that for 2003. Furthermore, given the infrequent precipitation events during both years, a trend relating sapflow with precipitation was weak. The coefficient of determination was $r^2 = 0.002$ ($P = 0.8784$) for 2002 and $r^2 = 0.32$ ($P = 0.0190$) for 2003. Despite its significance, the relationship between sapflow and precipitation for 2003 was biased because of numerous data points at 0 cm of precipitation. Moreover, trends relating sapflow with vapor pressure deficit were not significantly different from a zero slope. The coefficient of determination was $r^2 = 0.06$ ($P = 0.3425$) for 2002 and $r^2 = 0.10$ ($P = 0.2052$) for 2003.

Soil water availability is the most prominent limiting factor to transpiration, with other climatic variables such as temperature, wind, and vapor pressure deficit also being important [15,56–60]. Although our supplemental irrigation most likely helped to compensate for periods of limited water availability, we believe the trees exhibited elevated levels of sapflow because of their ability to develop an extensive root system and to withstand periods of limited water availability during increased temperature, wind, and vapor pressure deficit [22,61,62].

Therefore, our interpretation of the trends in Fig. 5 was that there were periods of additional need for water on the site despite our assertion that in 2003 the root systems developed sufficiently enough to exploit water from the groundwater aquifer. Braatne et al. [61] reported similar results showing that F_1 hybrids between *P. trichocarpa* and *P. deltoides*, along with their parents, exhibited reduced growth in response to limited water availability. Yet, these poplar genotypes most likely were able to maintain greater water potential while simultaneously exhibiting a balance between growth and water loss. We recognize comparisons among studies are never perfect because of differences in physical environment, genotypes, or both. However, we speculate there is a great potential for additionally increased water usage of hybrid poplars with increased levels of water availability. Future studies could be designed to test various levels of available water on sapflow of hybrid poplar.

3.3.3. Sapwood area × sapflow interactions

Linear models from the least-squares regression analysis relating sapflow with cross sectional area of sapwood explained the relationship best, according to coefficients of determination and significance probability values of each

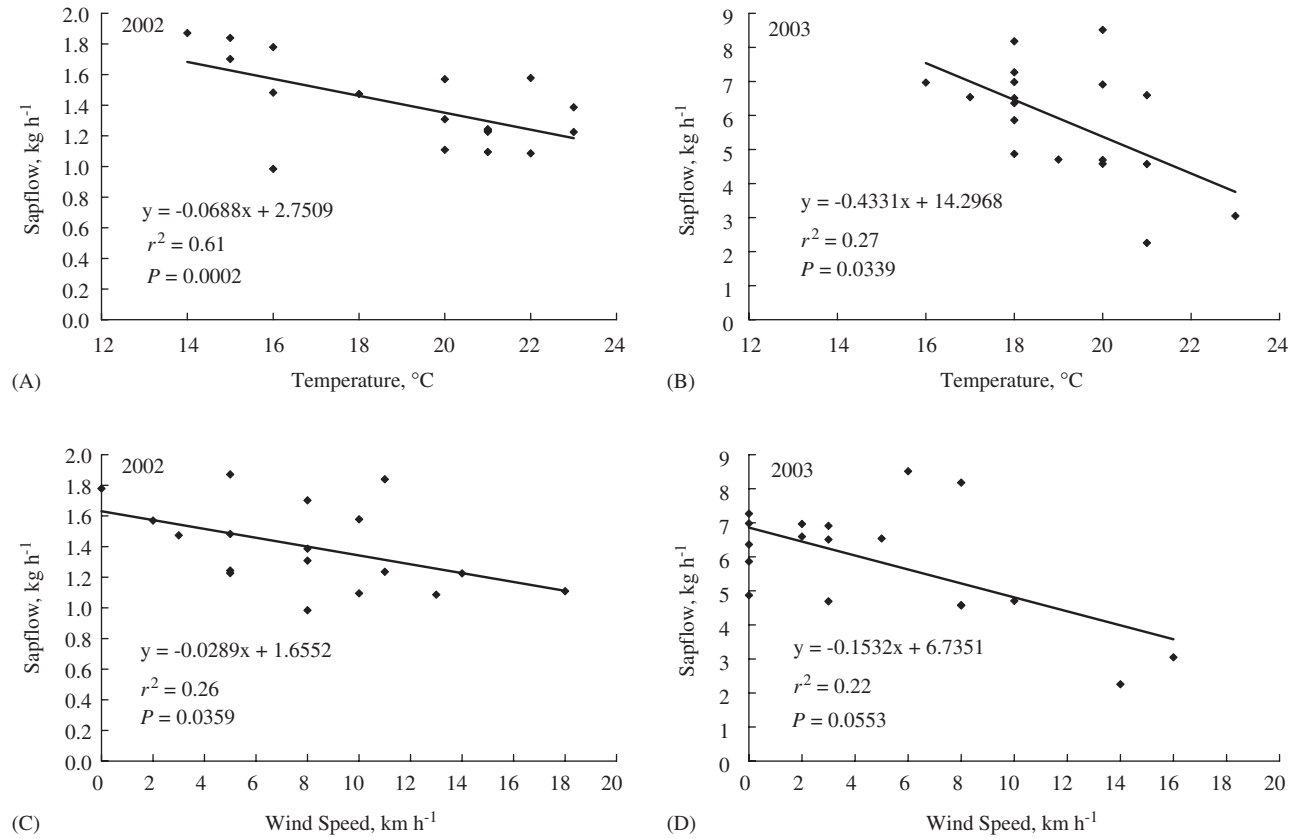

Fig. 5. Sapflow of hybrid poplar trees (*P. nigra* L. × *P. maximowiczii* A. Henry 'NM6') planted in 1999 versus temperature and wind speed in 2002 ($n = 15$) and 2003 ($n = 9$). Temperature and wind speed were collected at a regional airport weather station (KRHI) located approximately 5 km from the Rhinelander landfill test site.

regression. As was previously reported [15,45,63], sapflow increased with increasing cross sectional area of sapwood. The linear regressions of years considered independently were negligible. The coefficient of determination was $r^2 = 0.17$ ($P = 0.1436$) for 2002 and $r^2 = 0.41$ ($P = 0.0861$) for 2003. However, a positive linear trend fit the pooled data very well ($r^2 = 0.88$, $P < 0.0001$). Vose et al. [15] measured a similar trend across a range of species, including *P. deltoides*, and reported a coefficient of determination of $r^2 = 0.73$.

3.3.4. Stand level extrapolations of sapflow

We extrapolated individual tree sapflow values to stand level estimates in order to provide a prediction of the potential water usage of clone NM6 throughout the entire growing season in northern Wisconsin. Although other methods are available [64,65], our extrapolations were derived by using a mean-tree approach [15,41,66,67]. We believed this method was valid given the relative homogeneity of diameter, form, and growth rate of the trees, which supported the assertion that the sampled trees were representative of the other trees in the plantation [35]. In addition, Telewski et al. [68] reported for *Populus* trees less than 5 years of age that sapwood comprised almost all stemwood. Thus, we considered variations in the amount of sapwood among trees to be negligible. We tested bark thickness on sixteen sample trees during 2004 and found differences of <1% among trees (R. Zalesny, unpublished data). These differences further supported our assertion of having a representative sample of trees. In addition, climatic and edaphic variables were relatively uniform, which also should have made our sample representative of the overall population.

The total daily sapflow per tree was 34 and 136 kg tree^{-1} d^{-1} for 2002 and 2003, respectively. The 2002 estimate was comparable to and the 2003 estimate was greater than those previously reported. For example, Hinckley et al. [43] reported sapflow of 20 to 26 and 39 to 51 kg d^{-1} for trees of an F_1 hybrid between *P. trichocarpa* and *P. deltoides* with diameters of 8.3 and 15.1 cm, respectively. Martin et al. [69] reported sapflow ranging from 5 to 98 kg d^{-1} for Pacific silver fir (*Abies amabilis* Dougl. ex Loud.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) trees ranging in diameter from 16.9 to 40.1 cm. In addition, Knight et al. [45] reported sapflow ranging from 40 to 44 kg d^{-1} for 100-year-old *P. contorta* (var. *latifolia*) ranging in diameter from 20 to 26 cm.

The daily values summed over the 18-d sampling period gave estimates of 612 and 2448 kg tree^{-1} 18 d^{-1} for 2002

and 2003, respectively. Extrapolating these daily values to the stand provided estimates of 2.8 and 11.3 mm d^{-1} (28.3 and 113.3 Mg ha^{-1} d^{-1}) for 2002 and 2003, respectively, assuming a daily 24-h sampling period and 833 trees ha^{-1}. Thus, we estimated the total sapflow across a 125-d growing season to be 354 and 1 416 mm (3.54 and 14.16 Gg ha^{-1}) for 2002 and 2003, respectively, with the same assumptions as the previous extrapolations. We chose the 125-d growing season based on historical data ranging from 1971 to 2000, assuming a base temperature of 0 °C. The length of the growing season for Rhinelander, Wisconsin, ranged from 98 to 156 d, with a mean of 125 d. Our growing-season estimates generally are consistent with potential evapotranspiration (PET) values for the northern United States and southern Canada, where PET values range from 500 to 900 mm [70–72].

Other researchers of poplar have reported similar results. For example, Braatne [73] evaluated data from Hinckley et al. [43] and estimated yearly water use of hybrids between *P. trichocarpa* and *P. deltoides*. Braatne [73] reported rates of 625 to 880 mm yr^{-1}, 1.38 to 1.63 m yr^{-1}, and 2.01 to 2.26 m yr^{-1} for first year, second and third year, and fourth year and older trees, respectively. Likewise, Gordon et al. [14], citing personal communication with Dr. Paul E. Heilman of Washington State University, reported water usage of poplars in eastern Washington to be 1.4 m yr^{-1}, assuming trees were 5 years old and planted at a density of 1 750 trees ha^{-1}. In addition, Vose et al. [15] reported extrapolated yearly sapflow rates for a range of tree species, including *P. deltoides*, ranging from 1.51 to 6.86 Gg ha^{-1}, assuming a 180-d growing season and 350 trees ha^{-1}. Furthermore, most values for agronomic crops have been reported to be similar. Braatne [73] reported estimated yearly water use of annual vegetable and grain crops, alfalfa (*Medicago sativa* L.), and apples (*Malus* spp.) of 1.50 to 2.26 m yr^{-1}, 1.76 to 2.83 mm yr^{-1}, and 2.14 to 3.14 m yr^{-1}, respectively. In contrast, Russelle et al. [74] reported 4.9 Gg ha^{-1} of water was used by alfalfa during phytoremediation of inorganic nitrogen.

4. Conclusions and practical implications

Overall, the sapflow rates observed for clone NM6 growing in northern Wisconsin on soils contaminated with NH_3^+ were comparable to those previously reported for *Populus* under applications of phytoremediation and many short rotation woody crop systems. Thus, given the above-average performance of clone NM6 for rooting and aboveground growth relative to other clones in the North Central United States, we believe this clone and other superior-performing hybrid poplar genotypes exhibit great potential for phytoremediation applications where high water usage is a key trait for the success of the system. Also, the gains from breeding and selecting such genotypes promise substantial improvement because of the variability present in current populations of hybrid poplar. The increase in sapflow from the fourth to the fifth growing season expressed even greater potential as the trees increased belowground and aboveground growth. Future studies of this nature should measure sapflow during the entire growing season and across all years of the hybrid poplar rotation to identify specific periods of the greatest sapflow and temporal stages of sapflow throughout the development of the hybrid poplar planting.

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Disclaimer: Mention of trade names does not imply an endorsement by the Forest Service, United States Department of Agriculture.

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